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TENSILE PROPERTIES OF AW AND PWHT PN-229 WELD MATERIALS IN THE TEMPERATURE RANGE 20-300°C UNDER CONSTANT APPLIED STRAIN RATE CONDITIONS

Report No. 87-319-K

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ABSTRACT

A tensile test program has been carried out to characterize the plastic flow behaviour of both as-welded (AW) and post-weld heat treated (PWHT) PN-229 weld materials in the temperature range 20-300°C. At each test temperature, the specimens were deformed under constant applied strain rates of 10^{-4}, 10^{-3} and 10^{-2} s^{-1}. Results obtained indicate that both AW and PWHT materials were susceptible to jerky or serrated flow. However, the AW material was much more susceptible to this dynamic strain aging phenomenon, especially over the temperature range 150-200°C. The data also showed that the AW material exhibits a peak in tensile strength at about 200°C and a trough in ductility (ie, % RA and % Elongation) at about the same temperature. This finding indicates that the AW material should exhibit minimum fracture toughness properties at about 200°C. Furthermore, the results indicate that although the post-weld heat treatment used did not completely suppress serrated flow, it apparently eliminated sufficient amounts of interstitial solutes (responsible for serrated flow) from solid solution to improve the ductility of the PWHT material significantly. This improvement in ductility coupled with the reduction in tensile strength should give the PWHT material much better fracture toughness properties than the AW material over the temperature range 150-250°C.

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EXECUTIVE SUMMARY

TENSILE PROPERTIES OF AW AND PWHT PN-229 WELD MATERIALS IN THE TEMPERATURE RANGE 20-300°C UNDER CONSTANT APPLIED STRAIN RATE CONDITIONS

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OBJECTIVE: The main objective of the study was to characterize the susceptibility of as-welded (AW) and post-weld heat treated (PWHT) PN-229 weld materials to dynamic strain aging (jerky or serrated flow) and to obtain detailed flow curves for these materials. This information, together with data to be obtained from the other studies of the overall test program, will be used to assess whether PWHT should be recommended for the 22" lines of the Darlington Units 3 and 4.

MAJOR RESULTS OF STUDY:

1. Both AW and PWHT PN-229 weld materials were susceptible to serrated flow. However, the AW material was much more susceptible and this propensity to undergo dynamic strain aging was most prevalent over the temperature range 150-200°C.

2. The AW material exhibits a peak in tensile strength at about 200°C and a trough in ductility (% RA and % Elongation) at about the same temperature. This observation indicates that the AW material should show minimum fracture toughness properties at about the above temperature.

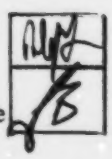
3. The post-weld heat treatment used (2 h at 620°C) apparently eliminated sufficient amounts of detrimental interstitial solutes from solid solution in the AW material to improve its ductility significantly at temperatures in the range 150-250°C. This improvement in ductility coupled with the reduction in tensile strength should improve the fracture toughness of the material significantly over the above temperature range.

4. The tensile data obtained proved to be very useful for delineating deformation conditions under which the AW material would exhibit minimum fracture toughness properties.

RECOMMENDATIONS

1. Additional tensile tests should be carried out at 100, 150 and 350°C to more fully characterize the flow behaviour of both AW and PWHT PN-229 weld materials.

2. The above tensile data should be complemented by carrying out a few additional fracture toughness tests.



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TENSILE PROPERTIES OF AW AND PWHT PN-229 WELD MATERIALS IN THE TEMPERATURE RANGE 20-300°C UNDER CONSTANT APPLIED STRAIN RATE CONDITIONS

1.0 INTRODUCTION

Data obtained from a materials test program/1/ carried out as part of the Darlington leak-before-break study showed that some non-stress relieved submerged arc weld (SAW) metal exhibited lower than expected fracture toughness at 250°C. The above test program also showed that a post-weld heat treatment (PWHT) of two hours at 620°C improved the 250°C fracture toughness and the room temperature Charpy impact energy of the weld metal. In light of the above findings, Task Group B-5 recommended/2/ that further investigation of the effects of PWHT on the SAW metal be carried out before PWHT is recommended for the 22" lines of Darlington Units 3 and 4. Moreover, information obtained from a recent literature review/3/ indicates that dynamic strain aging is responsible for, or at least related to the observed reduction in fracture toughness. Since serrated flow was observed in the 250°C tensile and fracture toughness tests, and since this manifestation of dynamic strain aging was most pronounced in the PN-229 weld material, a test program was proposed/4/ to evaluate the effect of PWHT on the toughness of weldments in SA106B piping material. The main objective of the present study, which is only part of the above proposed program, was to examine in detail the plastic flow behaviour of PN-229 materials over the temperature range 20-300°C. It was anticipated that results obtained from such a characterization process will help delineate the deformation conditions which would give rise to minimum fracture toughness properties. Furthermore, it was hoped that data obtained from the above proposed program can be used to quantify and/or validate the current practice of PWHT in accordance with the ASME code.

2.0 EXPERIMENTAL

Materials for the proposed test program were prepared using two documented weld procedures/5/. The #1 test coupons were made using the welding parameters used to prepare coupons for the previous study and a combination of welding processes of Ontario Hydro welding procedure PN-229-85. The #2 test coupons were fabricated using a modified welding procedure, but still within the essential variables of PN-229-85. This modified weld procedure was designed to give improved weld metal mechanical properties.

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Tensile specimens were machined from the weld coupons in such a manner that the tensile axis is parallel to the pipe axis and located at the 1/4-depth position relative to the pipe OD surface. The nominal gauge dimensions were 4.57 mm (0.180") in diameter and 19.05 mm (3/4") in length. This selection of subsize specimen geometry was chosen to ensure that the sample gauge length was comprised entirely of weld metal. The specimens were machined in conformance to ASTM specifications for round subsize specimens.

The tensile testing was carried out using a computer-controlled MTS servohydaulic Material Test System, as was the case for the previous tensile test program/6/. However, the test procedure used was somewhat different from that used previously. The main differences in the two test procedures were as follows:

1. The current tests were conducted under essentially constant applied strain rate conditions instead of the constant applied ram displacement rates used previously;

2. The specimen heating was accomplished using a split, three-zone resistance furnace instead of the single zone furnace used previously. The use of the three-zone furnace facilitated better temperature control and specimen temperature uniformity;

3. A continuous record of the load cell and ram displacement analog voltages were made using an X-Y chart recorder, along with a discrete digitized record of the above two voltages, as was done previously.

The above modifications to the previous test procedure were made in order that the serrated flow behaviour of the test specimens can be characterized fully.

3.0 RESULTS

3.1 Types of Serrated Flow Observed

As anticipated, under some of the test conditions investigated, serrated or jerky flow was observed, especially with the AW tensile specimens. Moreover, several types of serrated flow were observed. Representatives of the various types of serrated flow observed are presented in Figures 1-7. For comparison purposes, an example of a normal flow curve (ie, smooth plastic flow beyond the Luders strain) is presented in Figure 8. Figure 1 presents a flow curve that is fully serrated. In this example, the serrations occur at a relatively high "frequency" (frequency in the present context refers to the rate of occurrence of serrations with respect to sample strain or elongation) and the amplitude of the serrations first increases and then decreases with increasing plastic strain. Figure 2 presents an example of a fully-serrated curve in which the serrations have large but approximately constant amplitudes from yield to ultimate tensile stress levels. In addition, the serrations occur at a relatively low frequency. Figure 3 shows an example of a serrated flow curve which contains predominantly downward serrations or jerks which are designated as type B jerks in the literature/7,8/. Figure 4 shows a flow curve which is initially serrated but one in which the amplitude of the serrations decreases to very low values after a plastic strain of about 4%. Figure 5 presents a flow curve which is initially smooth but then develops serrated flow after about 5% plastic strain. Figure 6 presents a flow curve which is very similar to the one presented in Figure 5. However, in this example, the onset of serrations occurs

at a smaller plastic strain level of about 3%. Finally, Figure 7 shows a flow curve which is initially smooth but then develops periodic serrated flow after about 2% strain. The flow between the packets or "wave trains" of large amplitudes is also serrated, but is of very low amplitudes.

True stress-strain curves corresponding to the load vs ram displacement curves shown in Figures 1-8 are presented in Figure 9-16, respectively. It should be pointed out here that, in some cases, the true stress-strain curves do not reflect the true nature of the serrations as recorded in the raw load vs ram displacement data. This difficulty arises because the true stress-strain data were calculated using only a discrete record of the load cell and ram displacement analog voltages. Thus, if the data sampling rate was not much faster than the rate of occurrence of the serrations, then the full nature of the serrated flow can not be characterized by the discrete data set.

3.2 Tensile Properties of AW and PWHT PN-229 Weld Materials

A summary of the tensile test results is presented in Table I. Figures 17(a) and 17(b) present data which illustrate the variation of tensile strength with temperature for both AW and PWHT materials. The curves indicate that there is a peak in tensile strength at about 200°C for the AW material. However, for the PWHT material there appears to be a trough in tensile strength at 200°C. Figures 18(a) and 18(b) present data which illustrate the variation of 0.2% yield strength with temperature. The results show that the yield strength of both AW and PWHT materials decreases with increasing test temperature. Figures 19(a) and 19(b) present data which illustrate the variation of % reduction of area (% RA) as a function of temperature. The results indicate that, for AW material, there is a trough in the % RA vs temperature curve at about 200°C. Figures 20(a) and 20(b) present data which illustrate the % elongation as a function of temperature. The results show clearly that the % elongation of AW material exhibits a trough at about 200°C. It should be noted here that the data presented in Figures 17(a) to 20(a) were obtained from testing 1A and 2A coupon materials while those presented in figures 17(b) to 20(b) were obtained from testing coupon 1B materials.

4.0 DISCUSSION OF RESULTS

4.1 Serrated Flow Behaviour of AW Material

As anticipated, under certain deformation conditions of temperature and strain rate, the AW material exhibited serrated flow behaviour. In particular, the propensity for the AW material to undergo serrated flow was most prevalent in the temperature range 150-200°C. A variety of serrated flow was observed. However, the main types of jerky flow observed in this study have already been reported and described in the literature for mild steel/7-9/. The various types of serrated flow reported for mild steel have been divided into two basic types, designated as type A and type B. Type A serrated flow is characterized by the occurrence of jerks in the stress-strain curves which start from the onset of plastic deformation. Type B serrated flow, on the other hand, is characterized by the occurrence of jerks after the specimen has already undergone several percent of smooth plastic strain and by the downward nature (ie, drops below the general level of the stress-strain curve) of the serrations.

The general mechanism responsible for the occurrence of type A jerks in the stress-strain curves of body centred cubic metals and alloys, such as mild steel, is fairly well established/10-12/.

However, a detailed and widely accepted mechanism for the occurrence of type B jerks does not appear to exist. Work reported by Brindley and Barnby/8/ shows that in the case of coarse-grained mild carbon steel, the type B serrations were caused by the depletion of interstitial nitrogen in solid solution due to segregation at dislocations. The above finding indicates that only low nitrogen coarse-grained mild steel should exhibit type B serrated flow behaviour.

At a given test temperature, both the occurrence and the character of the serrations were very dependent on the applied strain rate. In testing at ambient temperature, the stress-strain curves were generally normal or smooth over the range of strain rates investigated. At 150°C, serrations were not observed at an applied strain rate of $10^{-2}s^{-1}$. However, with decreasing applied deformation rates, serrated flow appeared, with the amplitude of the serrations increasing with decreasing applied strain rates. At a test temperature of 200°C, serrations were observed at all three applied strain rates studied. Moreover, the appearance of the serrations at each applied strain rate was quite distinctive. At low ($10^{-4}s^{-1}$) strain rates, the serrations occurred at relatively high frequency with the amplitudes reaching a peak at intermediate plastic strain levels (see Figure 1). For intermediate ($10^{-3}s^{-1}$) strain rates, the serrations had a distinctive, large amplitude, downward jerk in character (see Figure 3). At the highest strain rate ($10^{-2}s^{-1}$) studied, the serrations had approximately constant amplitude throughout the whole range of plastic flow. For a test temperature of 250°C, the degree of serrated flow observed was much diminished compared to that observed at 200°C. At high strain rates, the stress-strain curves exhibited a few downward jerks in the first few percent of plastic flow. The ensuing plastic flow was relatively smooth. At intermediate strain rates, the stress-strain curves were smooth until a relatively large plastic strain level had been attained. Then type B serrated flow occurred. At low applied strain rates, the stress-strain curves were smooth until about 5% plastic strain had been achieved. Then a wave train of serrated flow occurred. However, at the highest temperature investigated, significant serrated flow was only observed at the lowest applied strain rate. This type of serrated flow was very similar to that observed at 250°C at the same applied strain rate.

The above described variation of serrated flow behaviour of the AW material with temperature and applied strain rate is similar to the dynamic strain aging behaviour of mild carbon steels reported in the literature/7-10/. For mild carbon steels, it is generally observed that serrated flow occurs primarily in the intermediate temperature range 100-300°C. At low temperatures, serrated flow is not observed because the interstitial solute atoms responsible for serrated flow diffuse too slowly to interact strongly with the moving dislocations. On the other hand, at high temperatures, the interstitial solutes are so mobile that they can follow or move with the dislocations so that no serrated flow is observed except possibly at very high strain rates. However, at intermediate temperatures, the mobility of the dislocations is strongly affected by the mobile interstitial solute atoms. Under such conditions, the types of serrated flow observed will be determined by how effectively the interstitial solutes can pin the mobile dislocations. At a given test temperature, the degree of pinning will be determined by such factors as the concentration of interstitial solutes, the material's microstructure and the applied deformation or strain rate. For the range of conditions examined in the present study, it appears that maximum pinning occurs at about 200°C at an applied strain rate of $1 \times 10^{-4}s^{-1}$.

4.2 Serrated Flow Behaviour of PWHT Material

The results presented in Table I and Figures 17-20 show clearly that a post-weld heat treatment of two hours at 620°C reduced the yield and tensile strengths of the weld metal significantly and

increased the ductility of the material substantially. Moreover, the data indicated that the post-weld heat treatment had removed significant amounts of detrimental interstitial solutes from solid solution in the weld metal since the serrated flow observed with the AW material was either eliminated or minimized. However, the PWHT material was not completely free of serrated flow behaviour. In testing at room temperature, serrated flow was observed at the lowest applied strain rate investigated (Figure 7). At a test temperature of 200°C, where the degree of serrated flow was maximum in AW material, the PWHT material exhibited significantly less serrated flow, if any, under comparable applied strain rates. At the highest temperature investigated, there was very little difference in deformation behaviour between the AW and PWHT materials. The only significant differences observed were that the AW material had considerably higher yield and tensile strengths than the PWHT material.

The above findings indicate that the post-weld heat treatment used should result in good fracture toughness properties for the PWHT material at the deformation conditions of temperature and strain rate where the AW material exhibits minimum fracture toughness properties. However, the significant reduction in yield and tensile strengths observed with the PWHT material should be analyzed to determine whether it will be of concern from a design strength point of view.

4.3 Variation of Yield Strength With Temperature

In general, the yield strength of the AW material decreases with increasing temperature. However, over the temperature range where serrated flow was most prevalent, the decrease in yield strength with temperature was minimal. Data obtained from detailed testing of mild steels/13/ indicate that the yield strength (usually the lower yield strength) actually exhibits a peak at the same temperature where the flow stress vs temperature curves exhibit a peak. But, in view of the small number of tests carried out and the nature of the material studied (ie, inhomogeneities in microstructures, etc), the inability to detect a small peak in the yield strength vs temperature curve in the current study is understandable.

The yield strength of PWHT material decreases approximately linearly with temperature at constant applied strain rate. In fact, for an applied strain rate of $1 \times 10^{-3} s^{-1}$, the yield strength vs temperature curve is very similar to that observed for Darlington PHT SA106B parent piping material tested at a similar strain rate. However, since the PWHT material exhibited some serrated flow at the lowest applied strain rate (ie, $1 \times 10^{-4} s^{-1}$) at all test temperatures examined, the low strain rate data set departs from linearity.

4.4 Variation of Tensile Strength with Temperature

In general, the tensile strength of AW material was higher at elevated temperatures than at ambient temperature, with the peak in strength occurring at about 200°C at all applied strain rates studied. The only exception to the above observation was the case of specimens tested at an applied strain rate of $1 \times 10^{-2} s^{-1}$ at 150°C. At this test condition, the tensile strength of the AW material was slightly lower than that observed at room temperature. However, the load vs extension curve for this test condition also appeared quite different from those observed at the other two applied strain rates (Figure 21). Although the curve in Figure 21 does not exhibit conventional serrated flow, it nevertheless contains several widely spaced, relatively large drops in the specimen load. At the present time, the underlying cause for this flow behaviour is not understood.

Although all three AW coupon materials showed very similar serrated flow behaviour, the tensile strength of the 1B material was measurably less than those of the 1A and 2A materials over the temperature range 150-250°C where dynamic strain aging was most pronounced. The test results also indicate that for all intent and purposes, the 1A and 2A coupon materials were identical. On the surface, the above results appear incongruous in view of the fact that weld coupons 1A and 1B were supposed to be identical since they were made by the same weld procedure while coupon 2A was made by a modified procedure/5/. However, since the tensile specimens were machined from the 1/4-depth position of the weld, a location where the settings for the SAW filler passes were not all that different between the two weld procedures, the similarity in mechanical properties found for the 1A and 2A coupon materials may not be all that surprising. On the other hand, the difference in tensile strengths found between the 1A and 1B materials is unexpected. A plausible explanation for the measurably lower tensile strength of the 1B material is that it has a lower concentration of interstitial solutes in solid solution than the 1A and 2A materials.

In the temperature range 150-200°C, the tensile strength of AW material was very sensitive to the applied strain rate. More importantly, the tensile strength showed a pronounced negative strain rate sensitivity at these two temperatures. This negative strain rate sensitivity is a direct result of dynamic strain aging and the explanation for this phenomenon is well established in the literature/13,14/.

In general, the tensile strength of PWHT material first decreases and then increases with increasing test temperature. The minimum in tensile strength occurred at about 200°C, at all applied strain rates investigated. Comparison of the current data with those observed in a previous study/6/ for parent SA106B piping material indicates that the shape of the two curves is very similar, although the PWHT material had significantly lower tensile strengths. More importantly, the post-weld heat treatment used lowered the strength of the AW PN-229 material significantly and should allow it to achieve good toughness properties over the entire range of temperatures investigated.

4.5 Variations of Percent Reduction of Area and Percent Elongation with Temperature

The ductility of AW material, as measured by the % RA and % elongation parameters, exhibits a steep decline with temperature until a temperature of about 200°C is reached (see Figures 19 and 20). Then the ductility begins to improve. This trough in the ductility curve occurs at a temperature where the tensile strength vs temperature curve shows a peak. From the above-mentioned observations, it is evident that the AW material should exhibit minimum fracture toughness properties at about 200°C. Data presented by Miglin et al/15/ for AW E8015-C3 submerged metal arc weld deposits indeed show a minimum in J_{IC} values at about 200°C.

In contrast to the above, the ductility of PWHT material remains approximately constant with temperature until about 200°C. Then it begins to show a decline with temperature to 300°C, the highest temperature investigated. This behaviour of the % RA and the % elongation parameters of PWHT material indicates that it should have good fracture toughness properties over the entire temperature range of interest, consistent with previous observations/1,16/ of the recovery of good fracture toughness after post-weld heat treatment.

5.0 CONCLUSIONS

1. Serrated or jerky flow was observed in tensile testing of both AW and PWHT PN-229 weld materials. However, the occurrence of serrated flow was most prevalent in AW material over the temperature range 150-200°C.

2. The flow stress of AW PN-229 material is negative strain rate sensitive over the temperature range 150-200°C, with the magnitude of the negative rate sensitivity greater at the lower temperature.

3. The AW material exhibits a peak in tensile strength with temperature at about 200°C and a trough in ductility (ie, % RA and % elongation) at approximately the same temperature. This finding indicates that the AW material should exhibit minimum fracture toughness properties at about this temperature.

4. The post-weld heat treatment used (2 h at 620°C) did not completely eliminate serrated flow in the weld material. However, the heat treatment apparently eliminated sufficient detrimental interstitial solutes from solid solution to give the PWHT material much better ductility. This improvement in ductility coupled with the reduction in strength should give the PWHT material better fracture toughness properties than the AW material over the temperature range 150-250°C.

5. The tensile data obtained indicate that there are no detectable differences in mechanical properties between the weld materials prepared by the two different weld procedures investigated. However, since the tensile specimens were prepared from the 1/4-depth position of the weld, a location where the settings for the SAW filler passes were not all that different between the two weld procedures, the above finding may not be all that surprising.

6. Although the AW material exhibited a trough in % RA and % elongation at about 200°C, the minimum value of 15.8% observed for the latter parameter was close to the room temperature code value of 18% for the transverse direction.

7. Data obtained from constant applied strain rate tensile testing over appropriately selected ranges of temperature and strain rate provide a good data base for the selection of test parameters in fracture toughness testing.

6.0 RECOMMENDATIONS

1. Additional tensile tests should be carried out at 100, 150 and 350°C to more fully characterize the flow behaviour of both AW and PWHT PN-229 weld materials.

2. The new tensile data should be complemented by carrying out a few additional fracture toughness (J_{IC}) tests.

7.0 ACKNOWLEDGEMENTS

The weld coupons were supplied by M.L. Lau of the Mechanical Design Department of the Design and Development - Generation Division. The two types of weld coupons investigated were fabricated according to a combination of weld procedures (consistent with OH weld procedure PN-229-85) specified by C. Gluck of the Mechanical Design Department of the Design and Development - Generation Division.

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TABLE I

SUMMARY OF TENSILE RESULTS FOR AW AND PWHT PN-229 MATERIALS

TEST ID	MATERIAL	TEMP (°C)	APPLIED STRAIN RATE (s^{-1})	-0.2% YS (MPa)	UTS (MPa)	% RA	% ELONG	SERRATED FLOW (Y/N)
CSW1	AW-1A	20	10^{-3}	390	493.4	71.3	30.6	N
CSW2	PWHT-1A	20	10^{-3}	314	452.1	71.5	30.6	N
CSW3	PWHT-1A	20	10^{-4}	317	443.9	69.8	31.0	Y
CSW4	AW-1A	20	10^{-4}	392	490.1	68.5	30.3	N
CSW5	AW-1A	20	10^{-2}	401	501.9	69.1	30.5	N
CSW6	PWHT-1A	20	10^{-2}	346	461.1	69.3	30.2	N
CSW7	PWHT-1A	20	10^{-3}	318	451.0	67.7	35.5	N
CSW8	PWHT-1A	20	10^{-4}	294	413.9	70.9	33.6	Y
CSW9	AW-1A	200	10^{-4}	349	636.1	51.2	22.1	Y
CSW10	AW-1A	200	10^{-2}	365	607.9	55.3	21.4	Y
CSW11	AW-1A	200	10^{-3}	364	626.1	55.0	20.6	Y
CSW12	AW-1A	250	10^{-4}	330	604.9	53.8	25.8	Y
CSW13	AW-1A	250	10^{-2}	368	610.7	50.9	21.7	Y
CSW14	AW-1A	250	10^{-3}	354	614.5	52.2	22.7	Y
CSW15	AW-1A	300	10^{-4}	300	585.5	59.9	27.6	Y
CSW16	AW-1A	300	10^{-2}	333	596.7	52.5	29.5	N
CSW17	AW-1A	300	10^{-3}	312	592.3	58.0	30.1	N
CSW18	PWHT-1A	200	10^{-2}	273	390.1	70.7	30.3	N
CSW19	PWHT-1A	200	10^{-4}	252	409.7	66.5	32.1	Y
CSW20	PWHT-1A	200	10^{-3}	261	394.0	69.0	29.7	Y
CSW21	PWHT-1A	300	10^{-4}	237	454.4	63.4	30.8	Y
CSW22	AW-1B	200	10^{-2}	360	567.7	52.5	18.8	Y
CSW23	AW-1B	200	10^{-4}	378	609.2	50.9	21.5	Y
CSW24	AW-1B	150	10^{-2}	354	485.2	59.5	25.5	N
CSW25	AW-1B	150	10^{-4}	388	598.2	53.3	19.2	Y
CSW26	AW-1B	150	10^{-3}	363	552.0	58.1	21.8	Y
CSW27	AW-1B	20	10^{-3}	396	496.1	68.6	27.4	N
CSW28	AW-1B	200	10^{-3}	351	581.3	54.4	21.6	Y
CSW29	AW-1B	200	10^{-2}	357	569.4	55.2	24.1	Y
CSW30	AW-1B	200	10^{-2}	343	572.7	50.2	18.3	Y
CSW31	AW-1B	150	10^{-2}	388	495.1	61.0	22.1	N
CSW32	PWHT-1B	20	10^{-4}	317	438.6	71.2	33.7	Y
CSW33	PWHT-1B	20	10^{-2}	337	464.5	71.7	34.6	N
CSW34	AW-2A	20	10^{-3}	407	505.3	65.6	27.9	N
CSW35	PWHT-2A	20	10^{-3}	327	453.6	71.6	31.8	N
CSW36	AW-2A	200	10^{-2}	378	605.9	51.0	18.4	Y
CSW37	AW-2A	200	10^{-2}	482	624.0	48.8	15.8	Y

TABLE I (CONTINUED)

TEST ID	MATERIAL	TEMP (°C)	APPLIED STRAIN RATE (s^{-1})	~0.2% YS (MPa)	UTS (MPa)	% RA	% ELONG	SERRATED FLOW (Y/N)
CSW38	PWHT-2A	200	10^{-2}	277	392.7	71.7	28.9	N
CSW39	PWHT-1B	200	10^{-2}	278	384.2	71.9	29.4	N
CSW40	PWHT-1B	200	10^{-4}	253	413.9	71.0	26.2	Y
CSW41	PWHT-1B	200	10^{-3}	261	394.0	71.2	27.5	Y
CSW42	PWHT-1B	300	10^{-3}	245	420.7	67.2	23.6	N
CSW43	PWHT-1B	250	10^{-3}	239	408.4	69.4	28.0	Y
CSW44	PWHT-1B	150	10^{-4}	284	398.8	71.4	27.4	Y
CSW45	AW-1B	150	10^{-4}	389	614.5	57.1	21.0	Y
CSW46	PWHT-1A	300	10^{-2}	234	400.9	67.9	26.4	Y
CSW47	AW-2A	200	10^{-4}	384	635.8	48.3	19.7	Y
CSW48	PWHT-2A	300	10^{-4}	234	459.6	62.1	28.3	Y
CSW49	AW-1B	250	10^{-3}	370	592.6	54.4	23.6	N

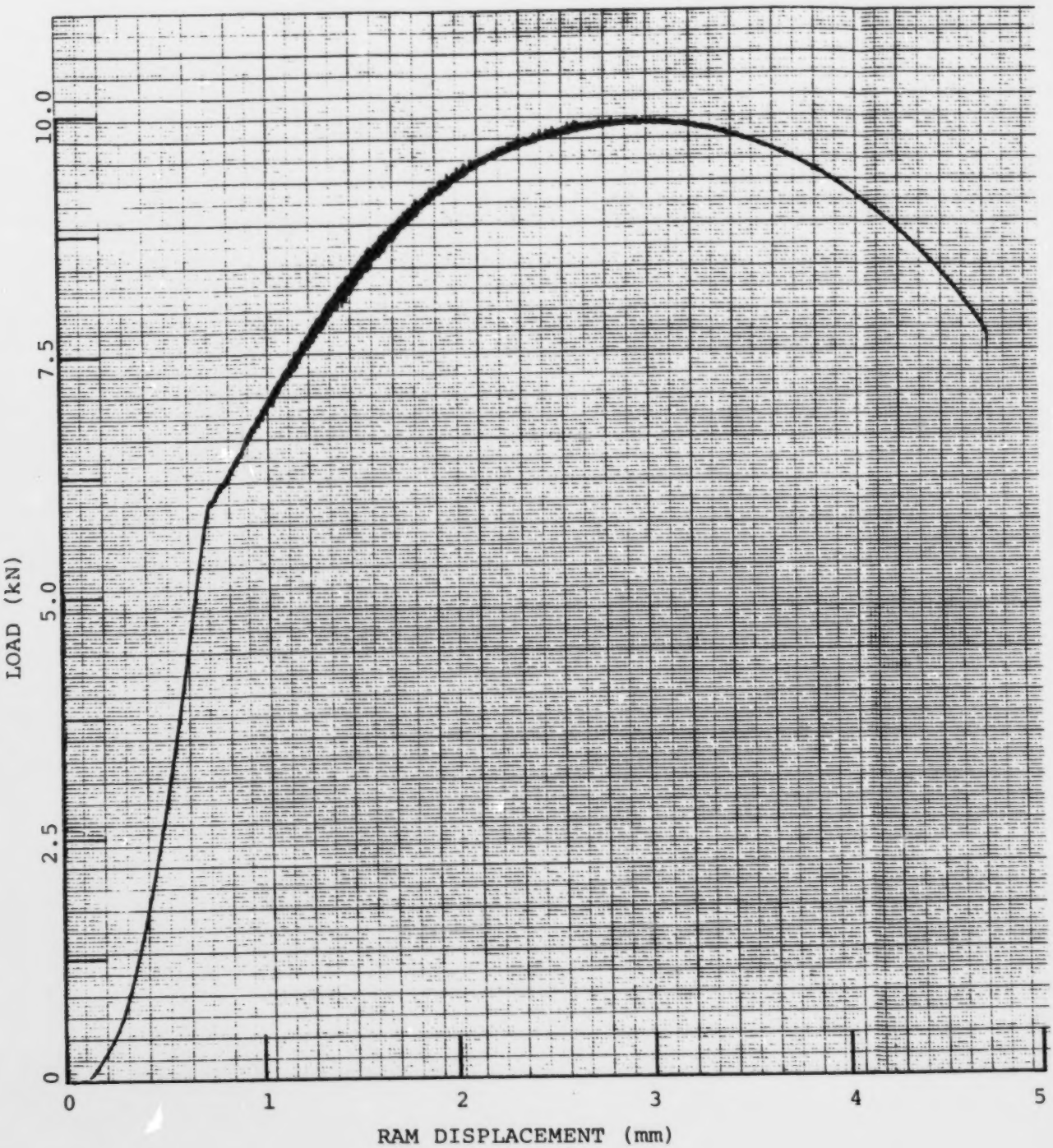

FIGURE 1: LOAD VS RAM DISPLACEMENT PLOT SHOWING A FULLY SERRATED FLOW CURVE. AW-18 MATERIAL WAS TESTED AT 200 C AT AN APPLIED STRAIN RATE OF 1E-4 1/S.

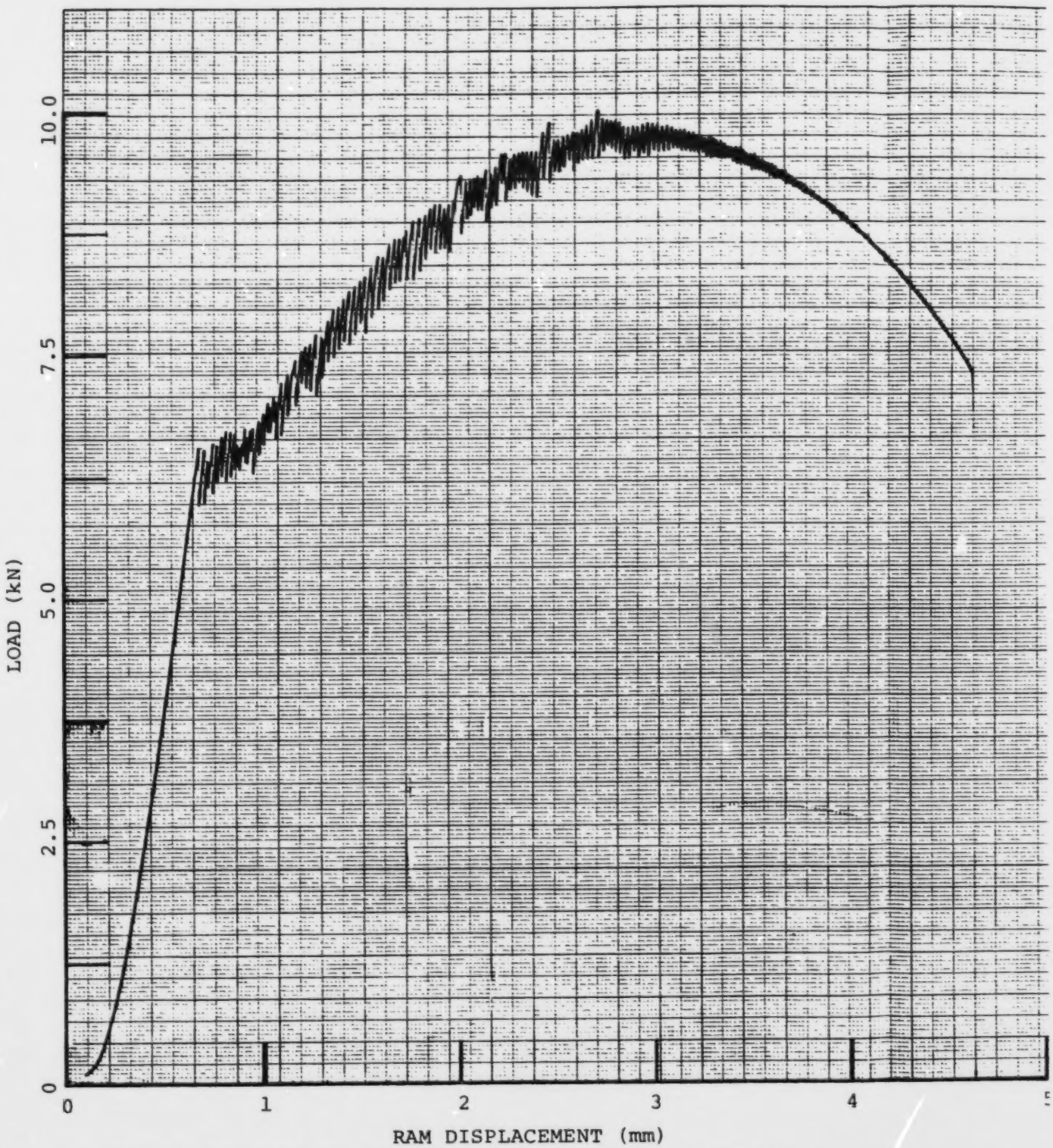

FIGURE 2. LOAD VS RAM DISPLACEMENT PLOT SHOWING A FULLY SERRATED FLOW CURVE WITH LARGE AMPLITUDE SERRATIONS. AW-18 MATERIAL WAS TESTED AT 150 C AT AN APPLIED STRAIN RATE OF 1E-4 1/S.

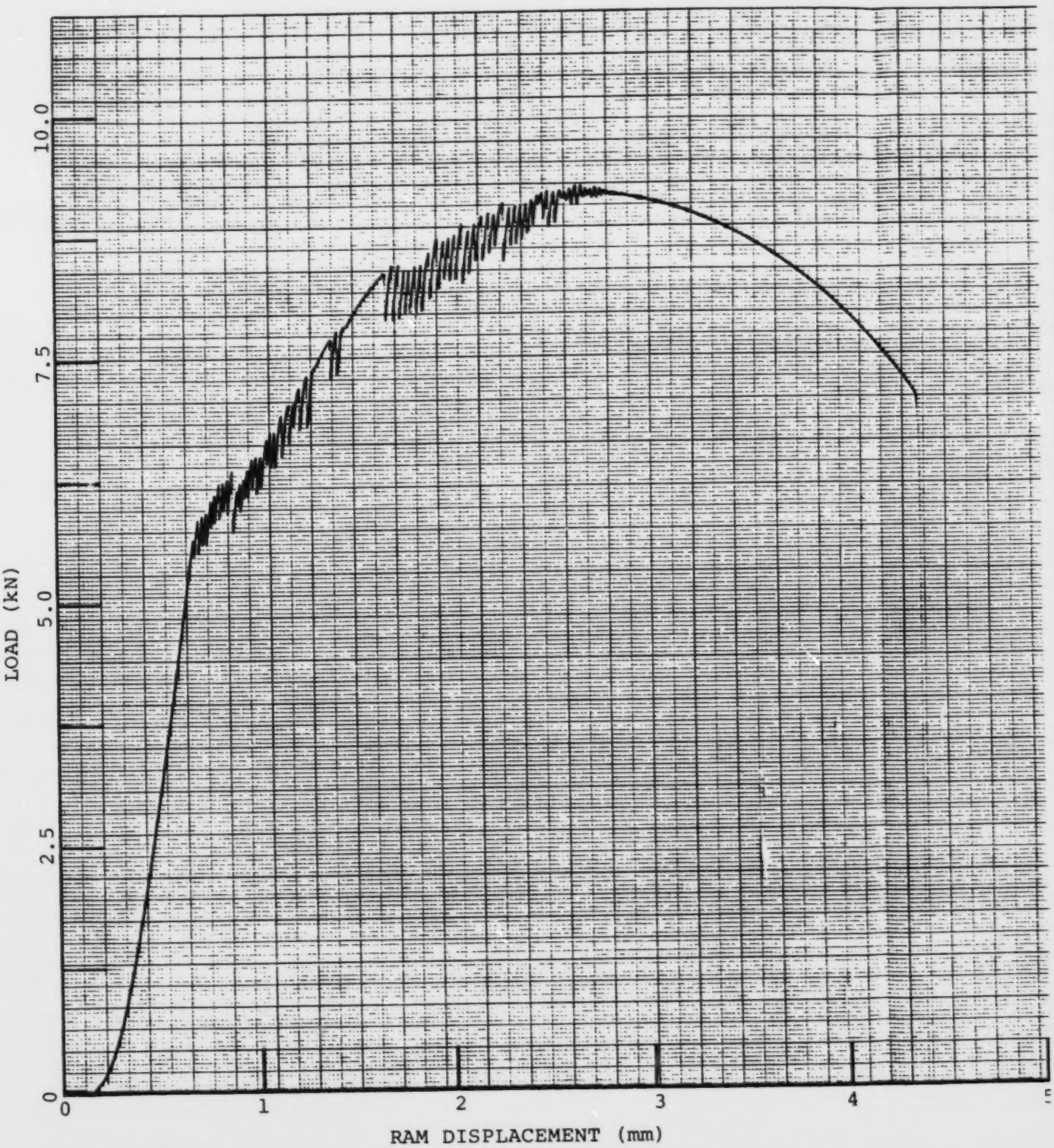

FIGURE 3: LOAD VS RAM DISPLACEMENT PLOT SHOWING A FULLY SERRATED FLOW CURVE WITH PREDOMINANTLY DOWNWARD JERKS OR SERRATIONS. AW-1B MATERIAL WAS TESTED AT 200 C AT AN APPLIED STRAIN RATE OF 1E-3 1/S.

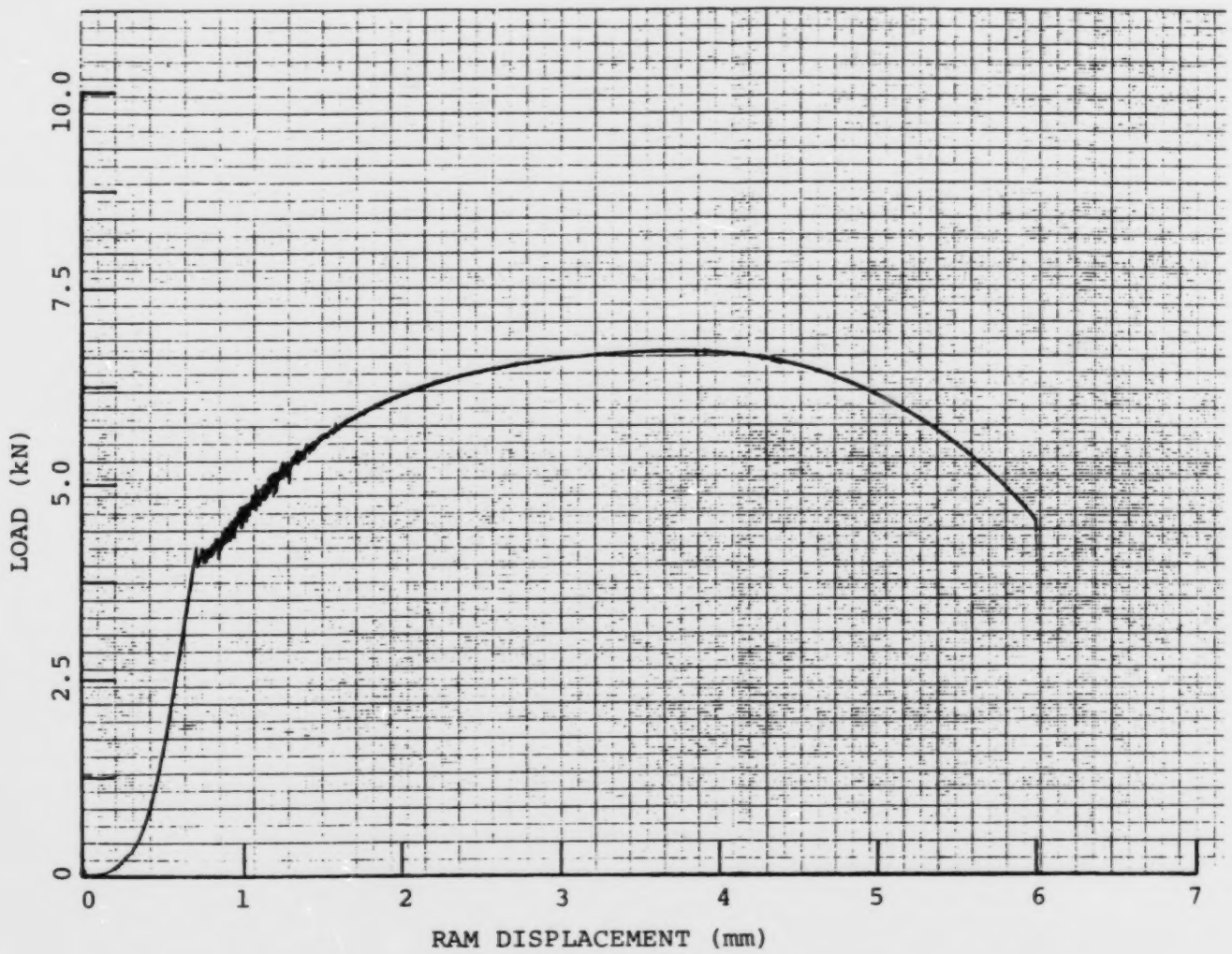

FIGURE 4: LOAD VS RAM DISPLACEMENT PLOT SHOWING A FLOW CURVE WHICH IS INITIALLY SERRATED. PWHT-1A MATERIAL WAS TESTED AT 200 C AT AN APPLIED STRAIN RATE OF 1E-4 1/S.

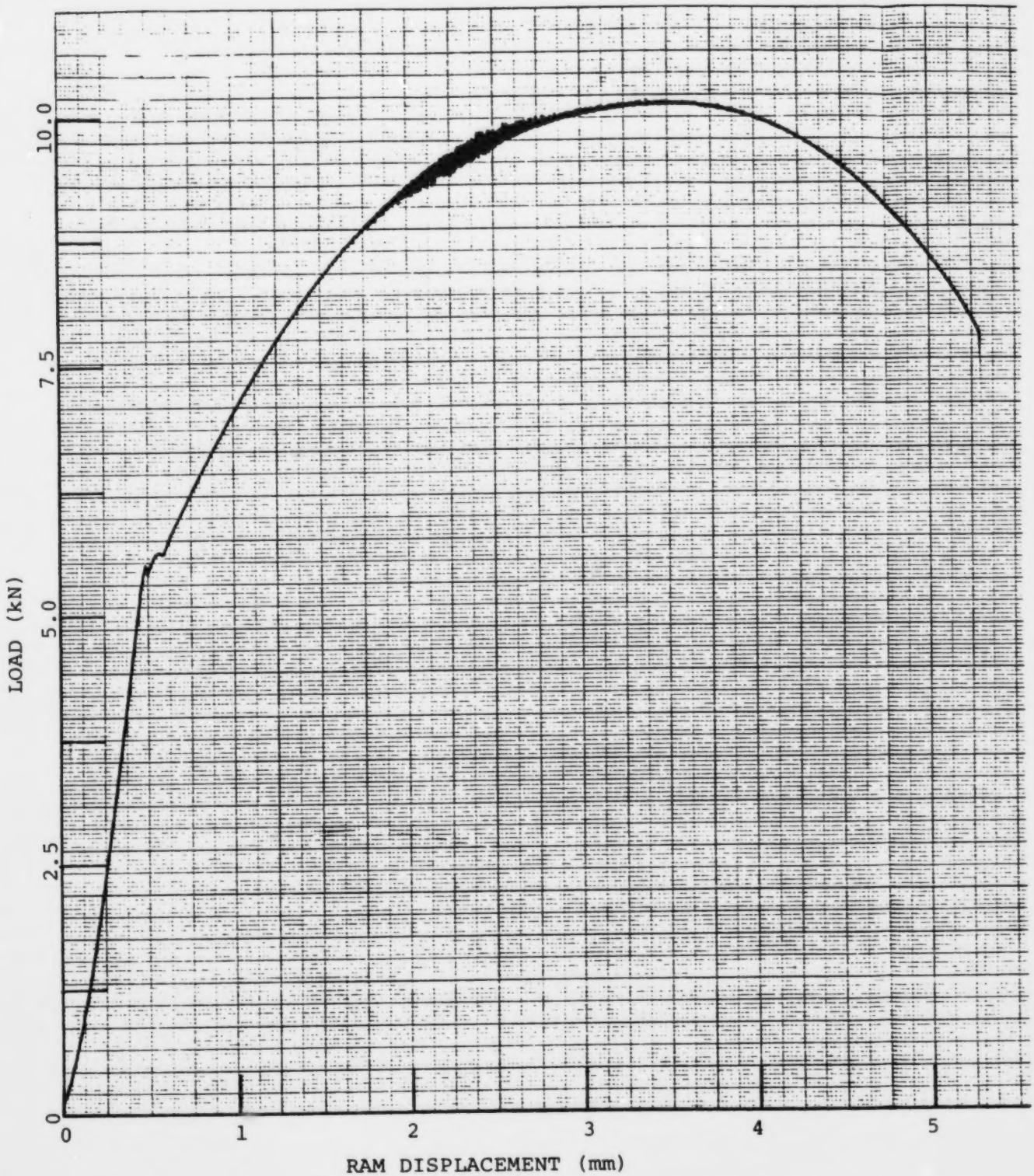

FIGURE 5: LOAD VS RAM DISPLACEMENT PLOT SHOWING A FLOW CURVE WHICH IS INITIALLY SMOOTH BUT THEN EXHIBITS SERRATIONS AFTER ABOUT 5% STRAIN. AW-1A MATERIAL WAS TESTED AT 250 C AT AN APPLIED STRAIN RATE OF 1E-4 1/S.

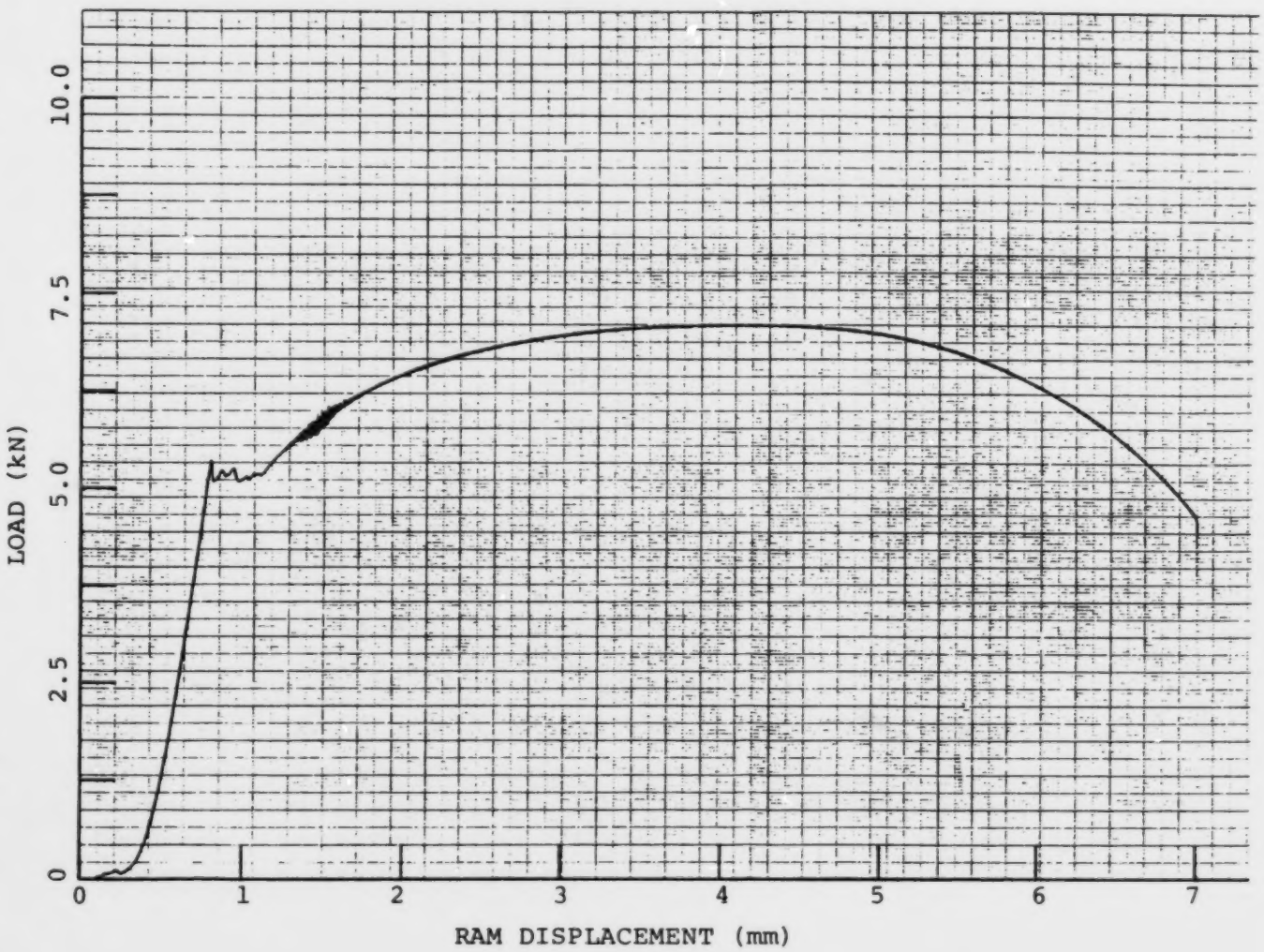

FIGURE 6: LOAD VS RAM DISPLACEMENT PLOT SHOWING A FLOW CURVE WHICH IS INITIALLY SMOOTH BUT THEN EXHIBITS SERRATED FLOW AFTER ABOUT 3% STRAIN. PWHT-1B MATERIAL WAS TESTED AT 20 C AT AN APPLIED STRAIN RATE OF 1E-4 1/S.

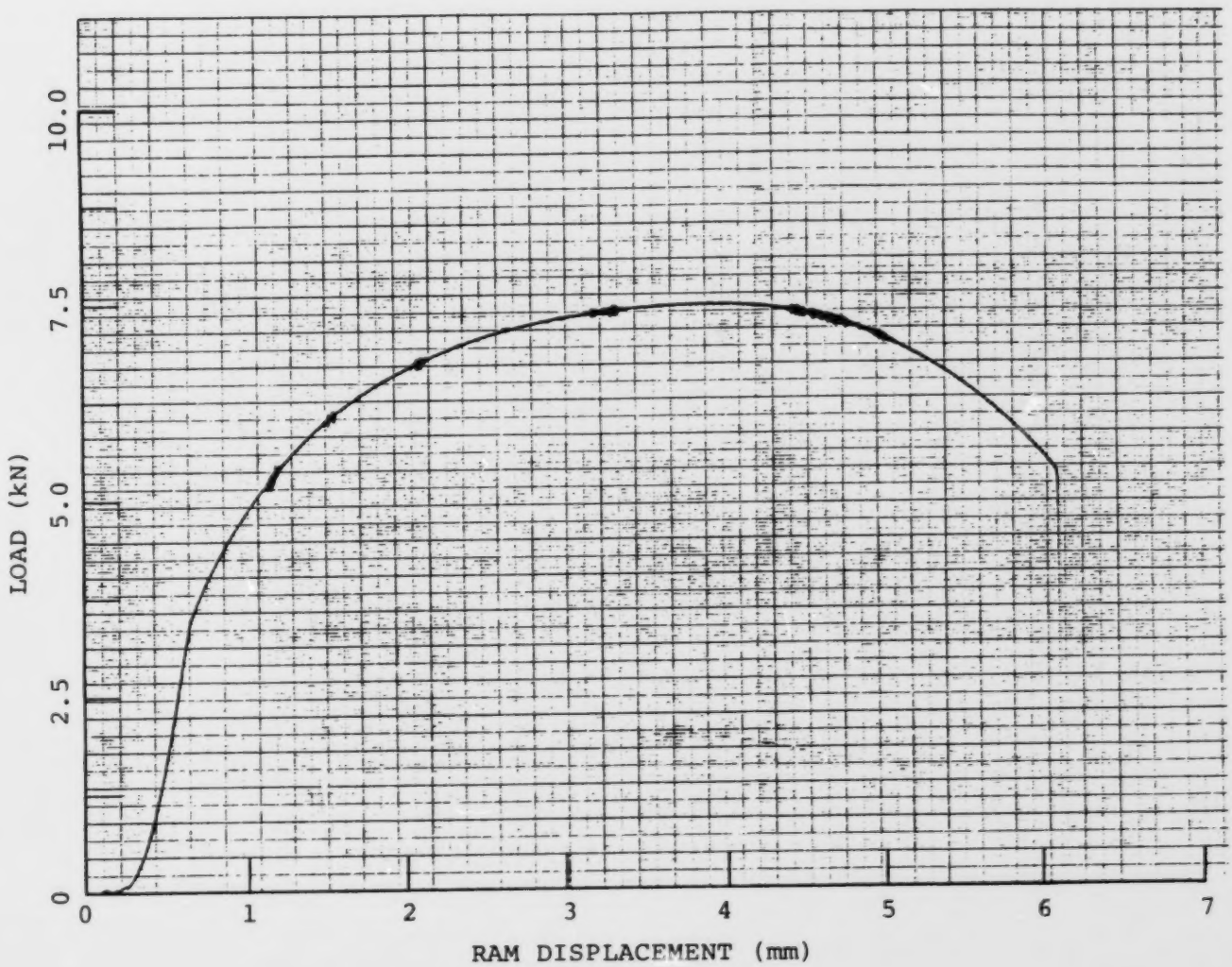

FIGURE 7: LOAD VS RAM DISPLACEMENT PLOT SHOWING A FLOW CURVE WHICH EXHIBITS PERIODIC SERRATED FLOW BEHAVIOUR. PWHT-2A MATERIAL WAS TESTED AT 300 C AT AN APPLIED STRAIN RATE OF 1E-4 1/S.

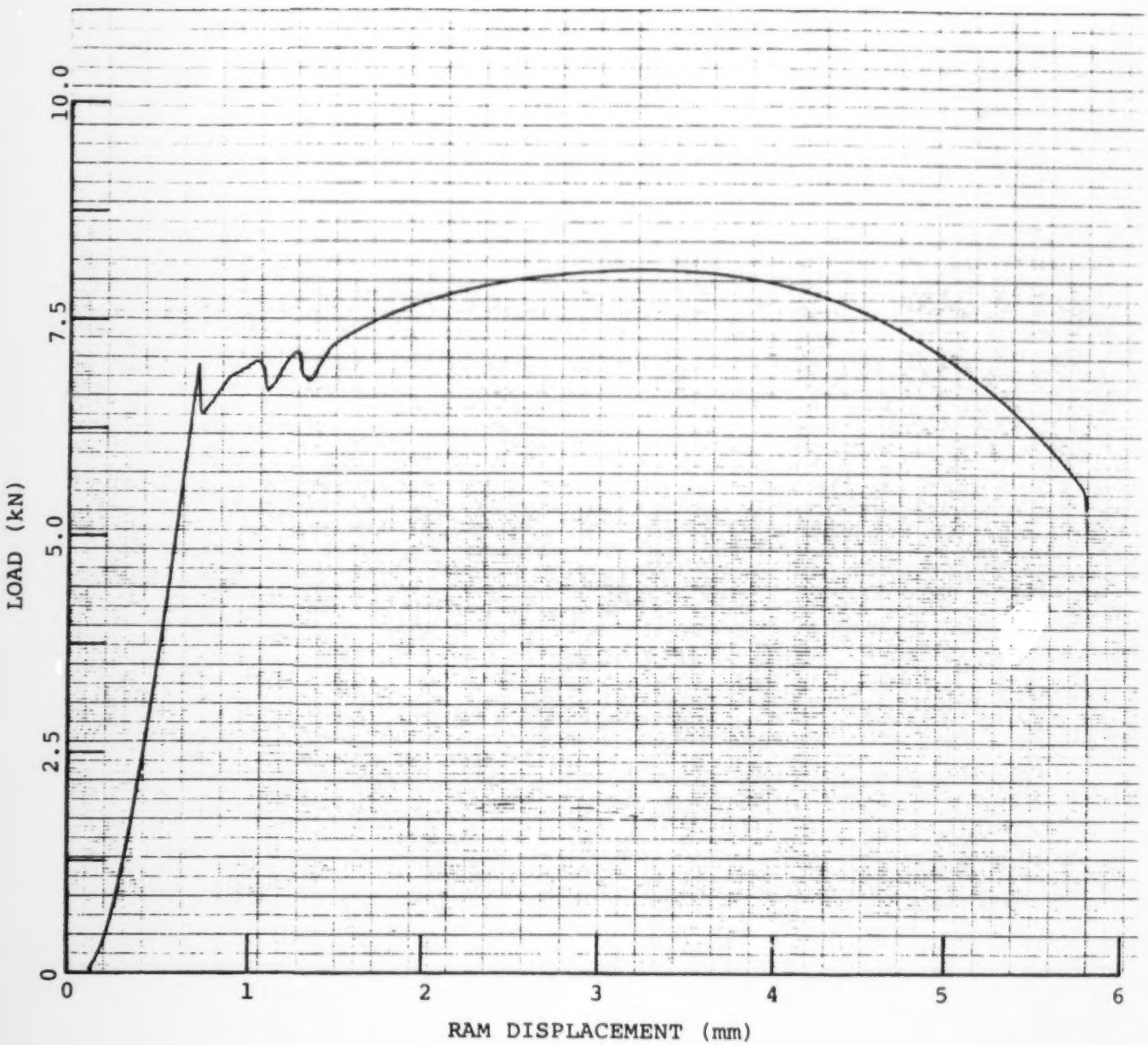

FIGURE 8: LOAD VS RAM DISPLACEMENT PLOT SHOWING AN EXAMPLE OF A NORMAL FLOW CURVE. AW-2A MATERIAL WAS TESTED AT 20 C AT AN APPLIED STRAIN RATE OF 1E-3 1/S.

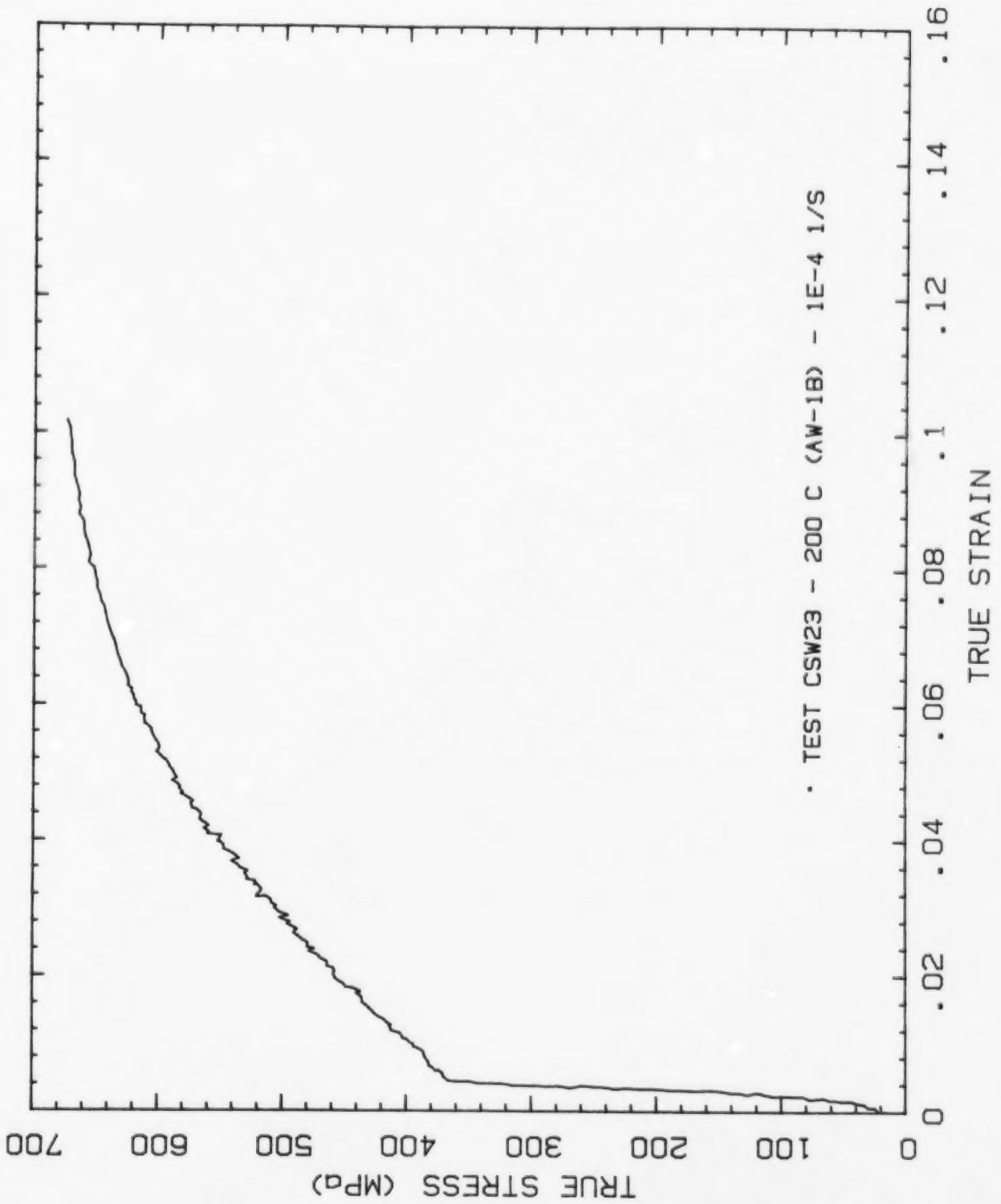

FIGURE 9. TRUE STRESS VS TRUE STRAIN PLOT CORRESPONDING TO THE RAW EXPERIMENTAL DATA PRESENTED IN FIGURE 1.

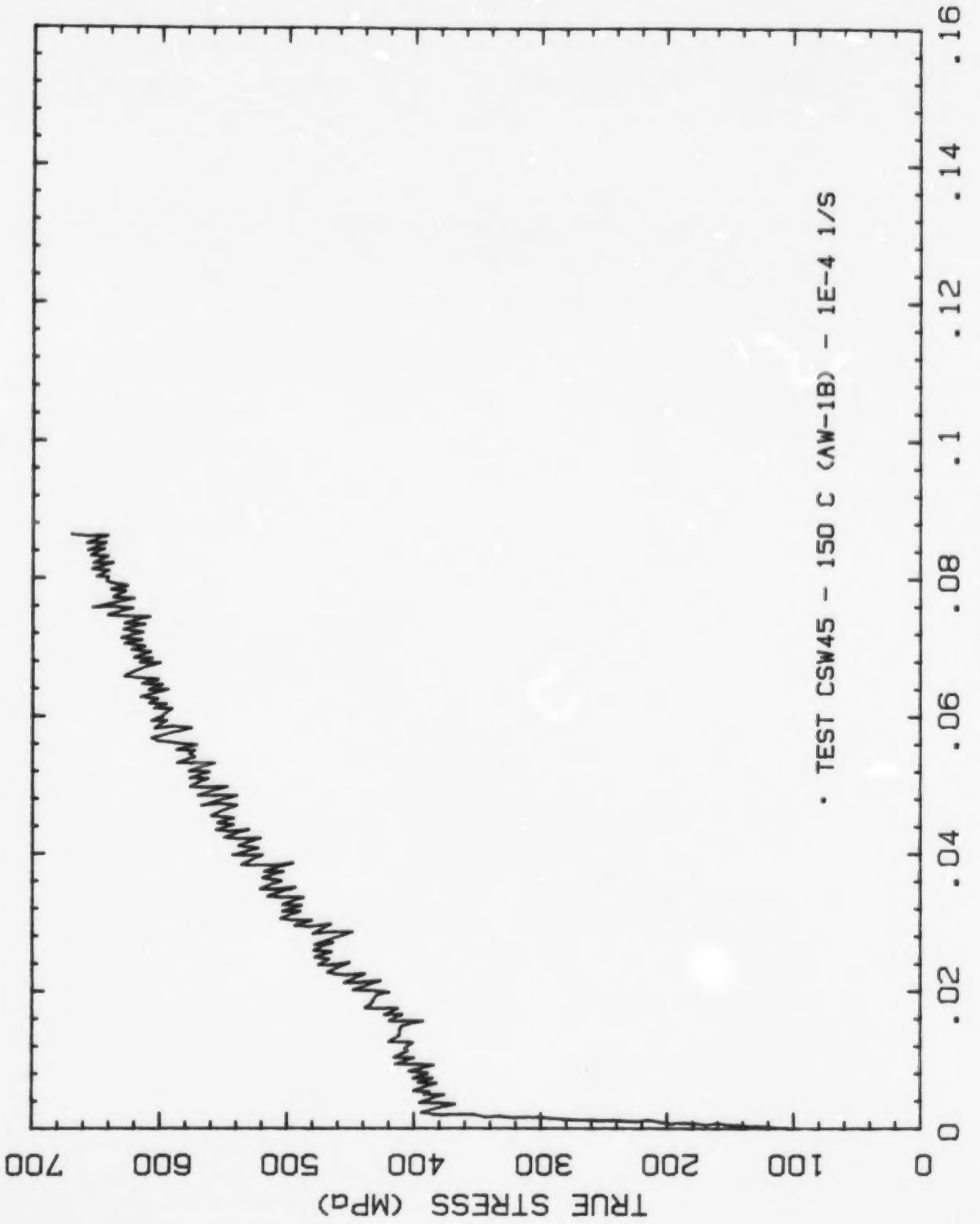

FIGURE 10. TRUE STRESS VS TRUE STRAIN PLOT CORRESPONDING TO THE RAW EXPERIMENTAL DATA PRESENTED IN FIGURE 2.

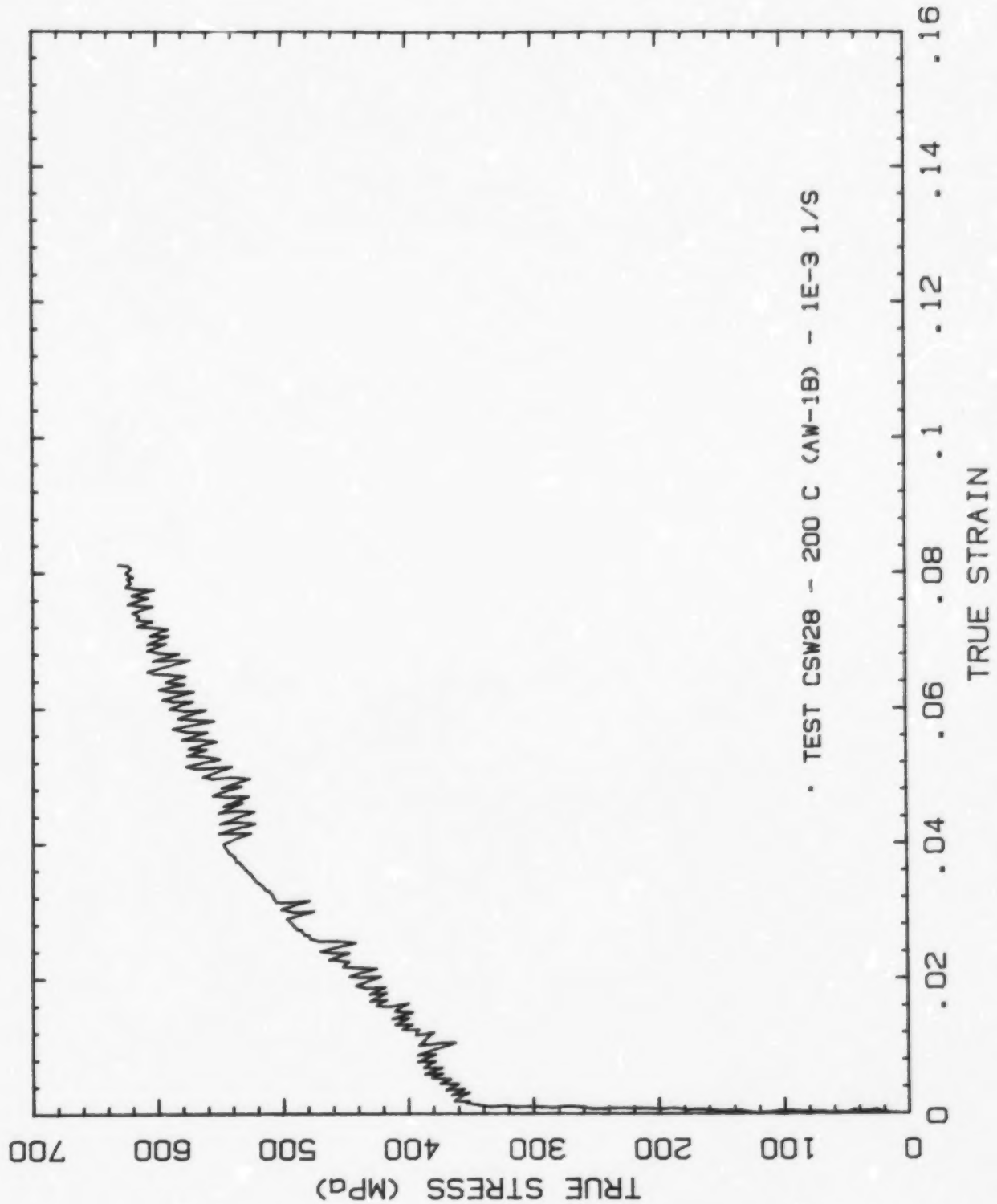

FIGURE 11. TRUE STRESS VS TRUE STRAIN PLOT CORRESPONDING TO THE RAW EXPERIMENTAL DATA PRESENTED IN FIGURE 3.

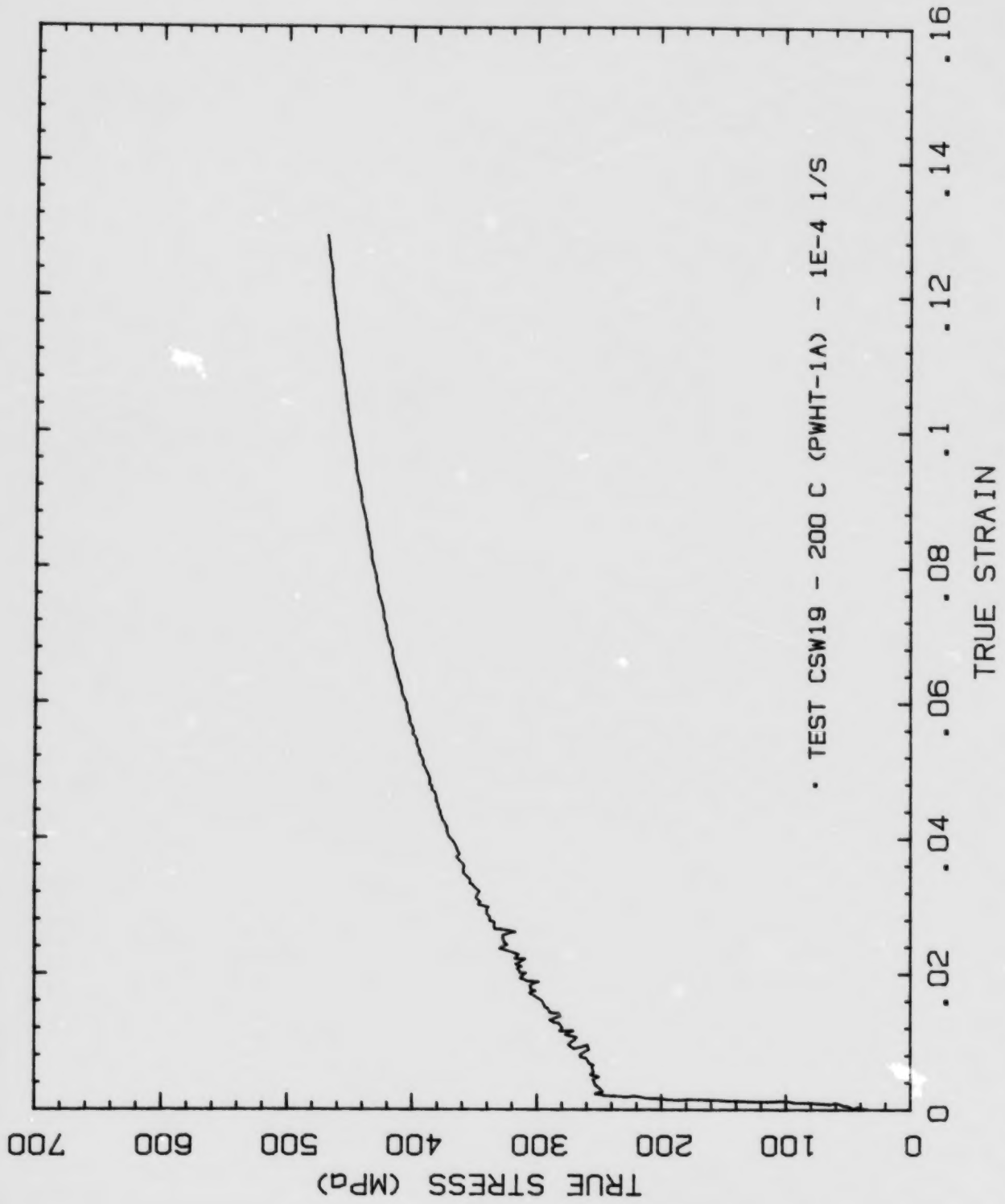

FIGURE 12: TRUE STRESS VS TRUE STRAIN PLOT CORRESPONDING TO THE RAW EXPERIMENTAL DATA PRESENTED IN FIGURE 4.

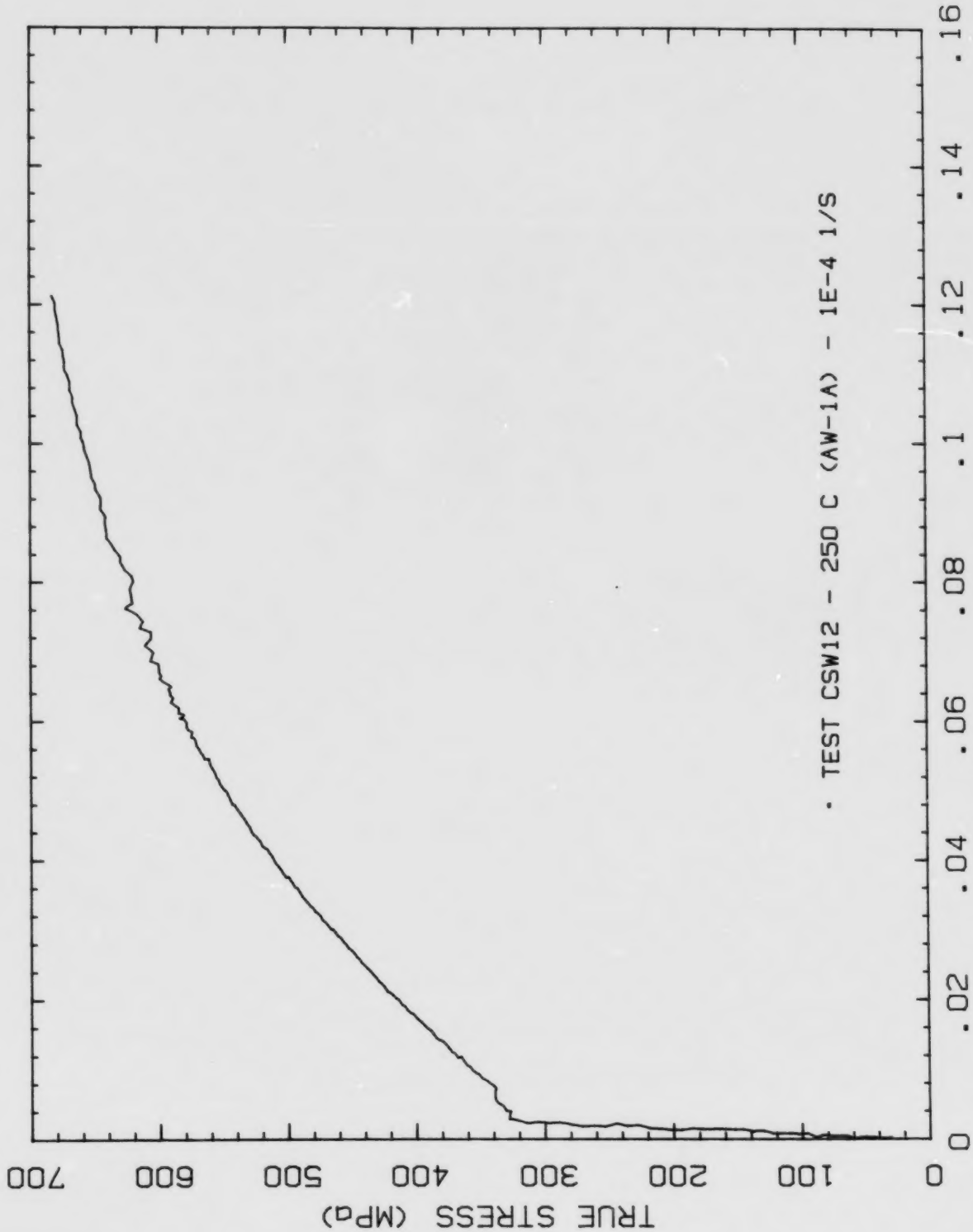

FIGURE 13. TRUE STRESS VS TRUE STRAIN PLOT CORRESPONDING TO THE RAW EXPERIMENTAL DATA PRESENTED IN FIGURE 5.

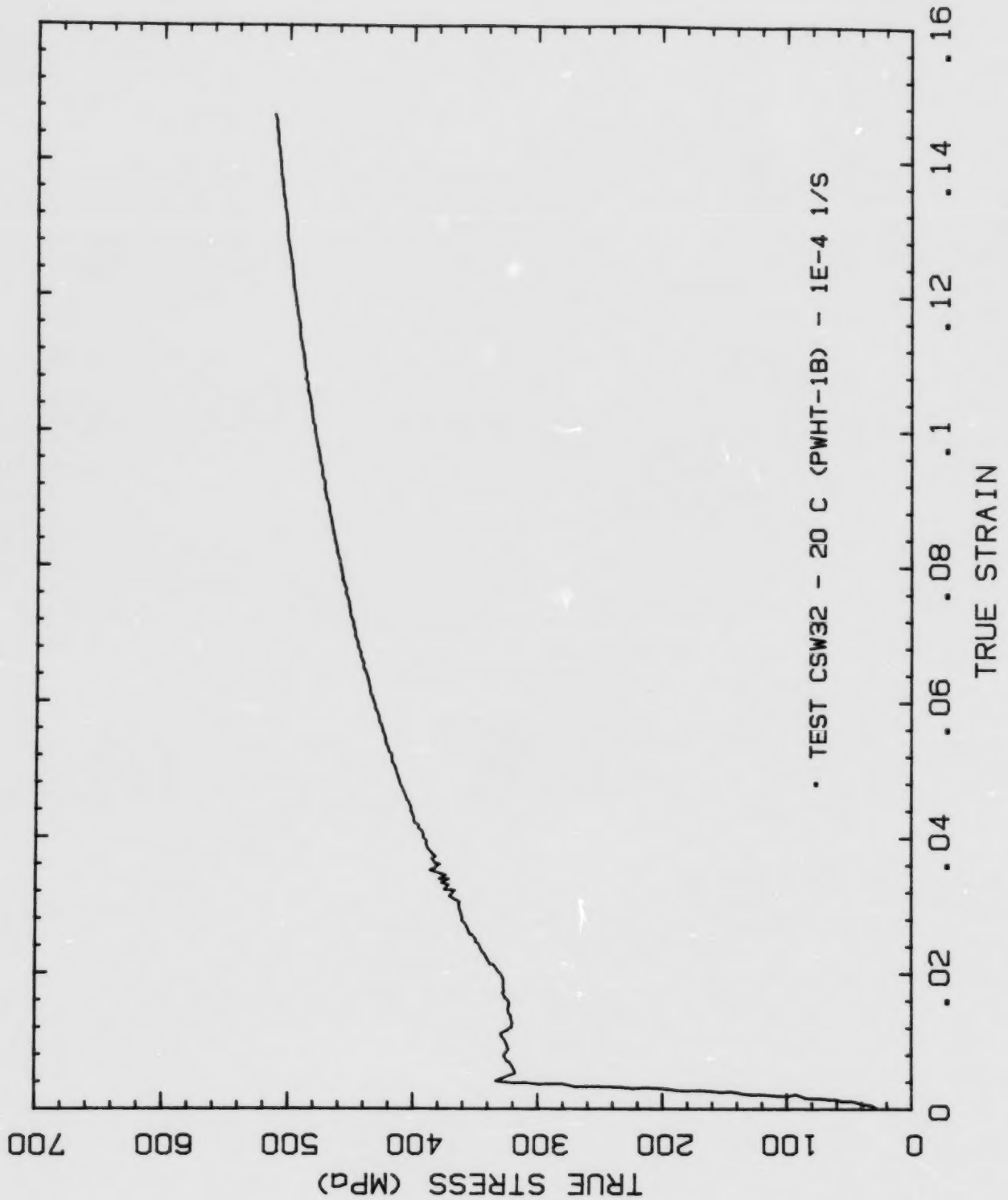

FIGURE 14: TRUE STRESS VS TRUE STRAIN PLOT CORRESPONDING TO THE RAW EXPERIMENTAL DATA PRESENTED IN FIGURE 6.

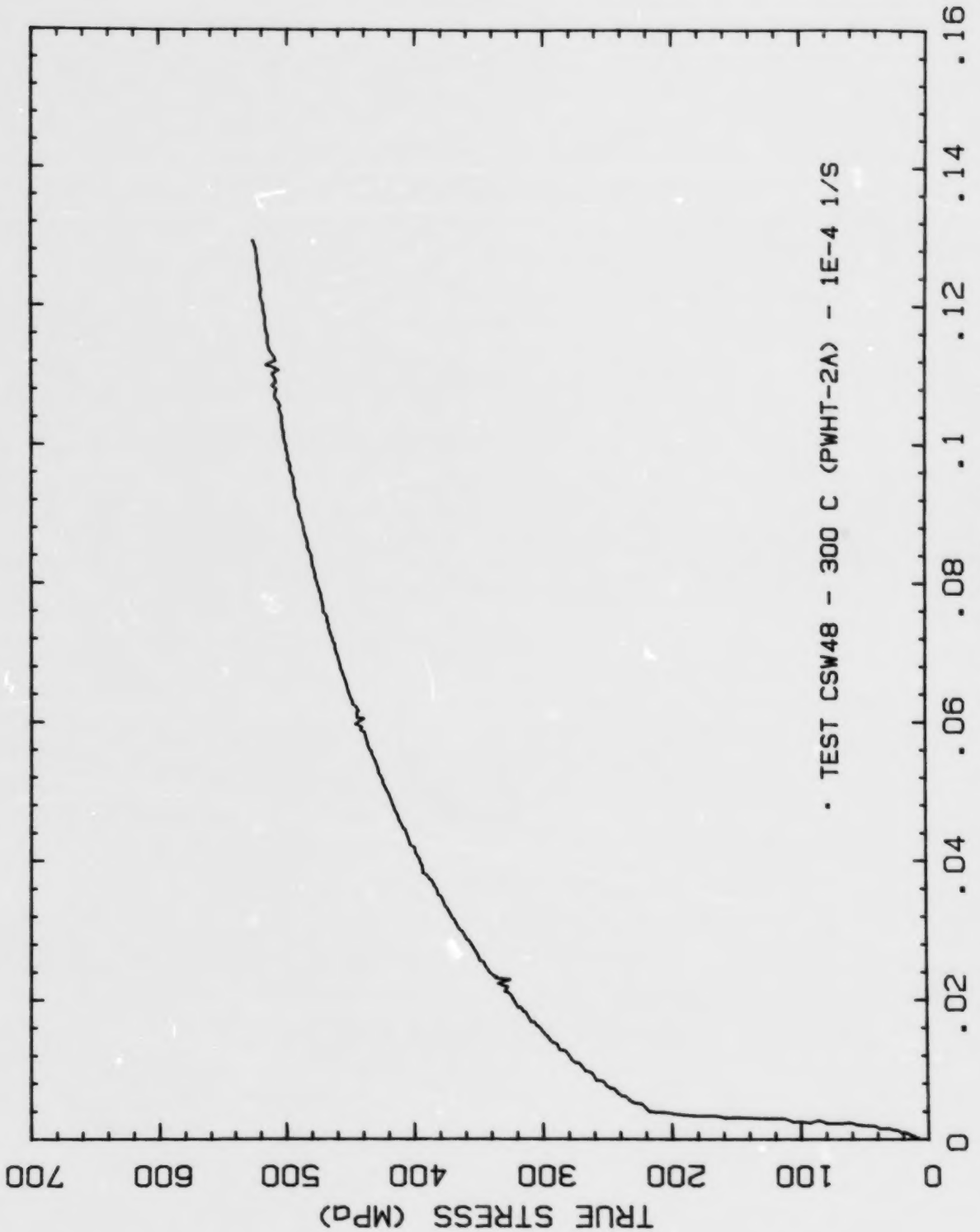

FIGURE 15: TRUE STRESS VS TRUE STRAIN PLOT CORRESPONDING TO THE RAW EXPERIMENTAL DATA PRESENTED IN FIGURE 7.

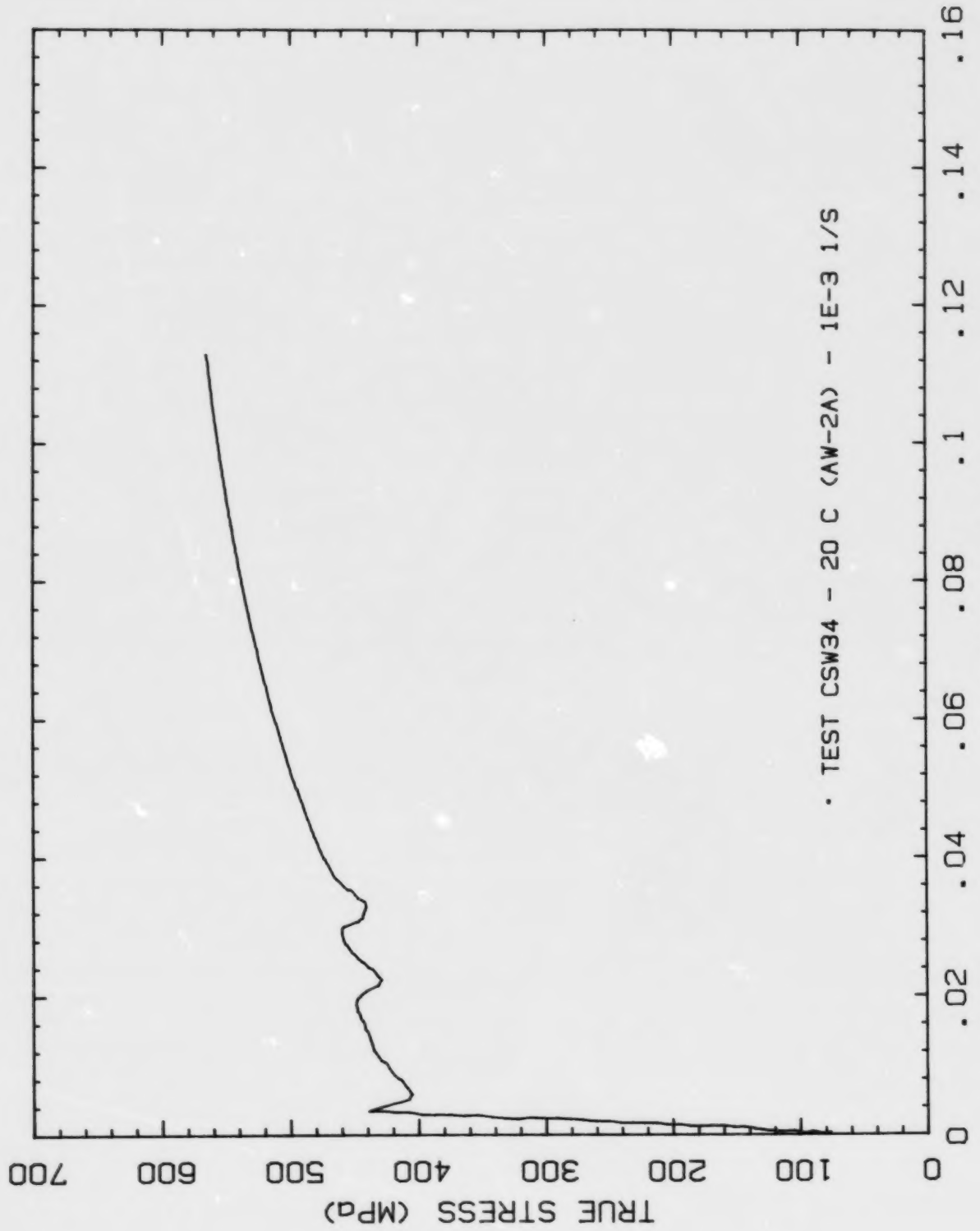

FIGURE 16: TRUE STRESS VS TRUE STRAIN PLOT CORRESPONDING TO THE RAW EXPERIMENTAL DATA PRESENTED IN FIGURE 8.

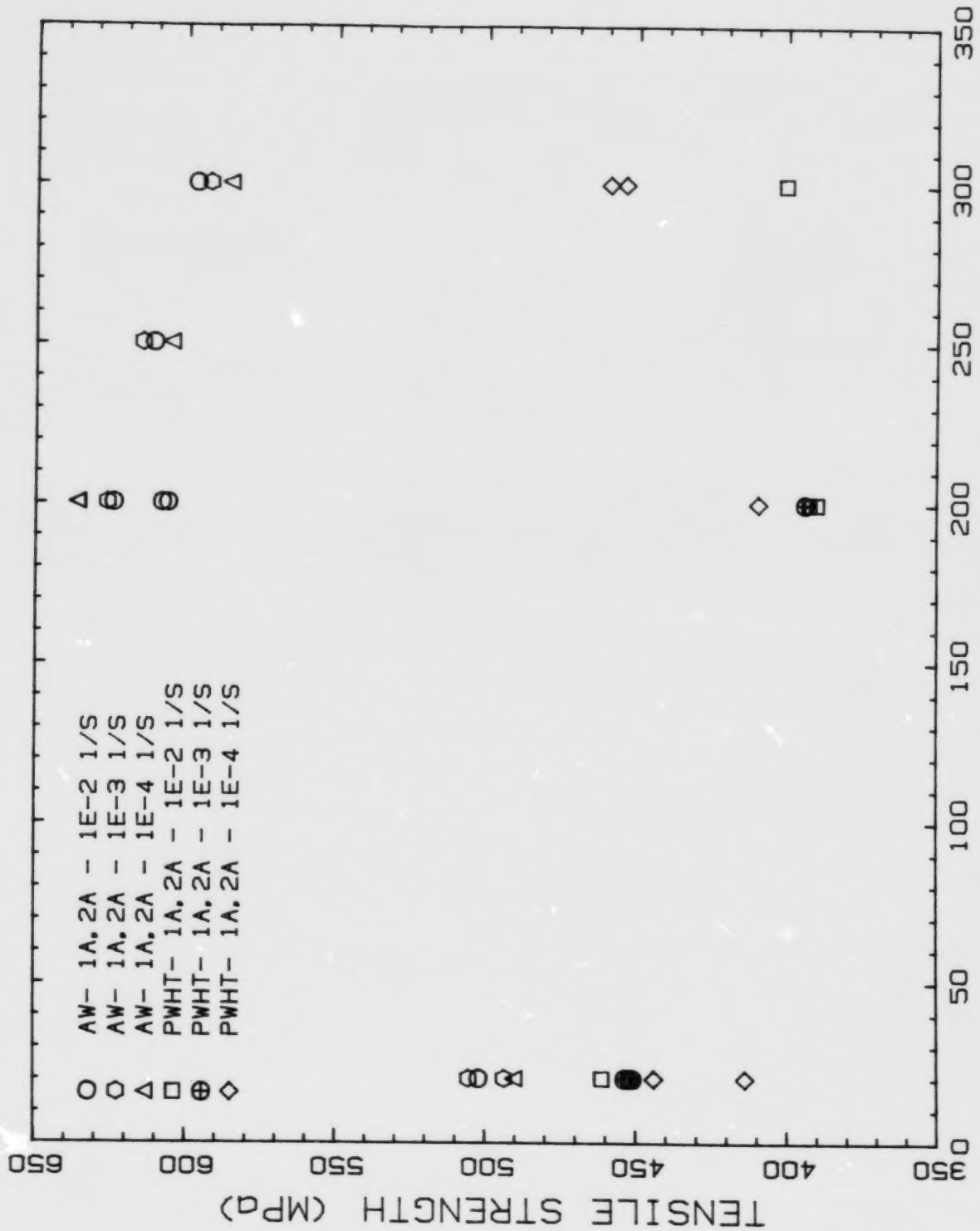

FIGURE 17(a): PLOTS ILLUSTRATING THE VARIATION OF TENSILE STRENGTH WITH TEMPERATURE AT CONSTANT APPLIED STRAIN RATE IN AW-1A, AW-2A, PWHT-1A AND PWHT-2A MATERIALS.

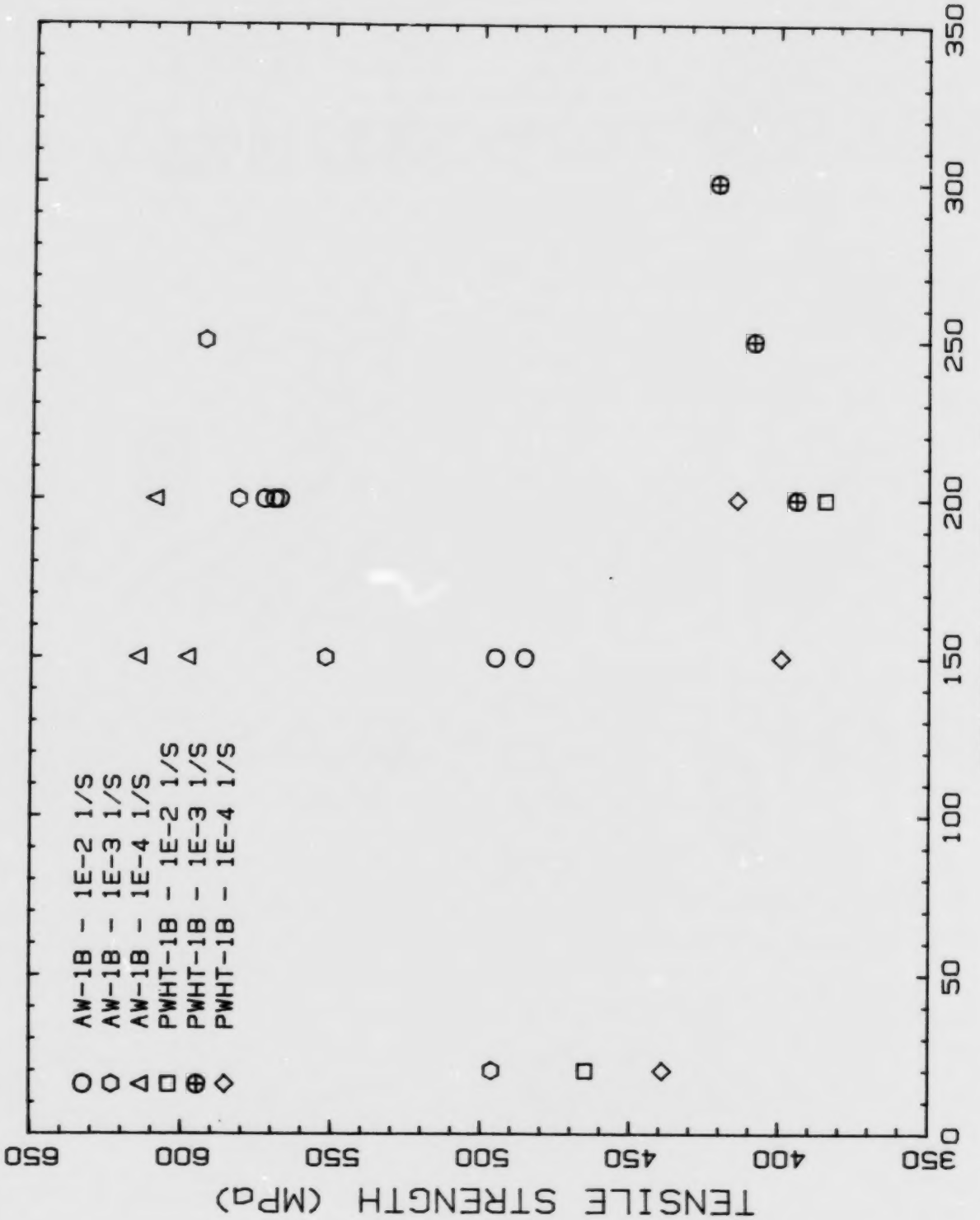

FIGURE 17(b): PLOTS ILLUSTRATING THE VARIATION OF TENSILE STRENGTH WITH TEMPERATURE AT CONSTANT APPLIED STRAIN RATE IN AW-1B AND PWHT-1B MATERIALS.

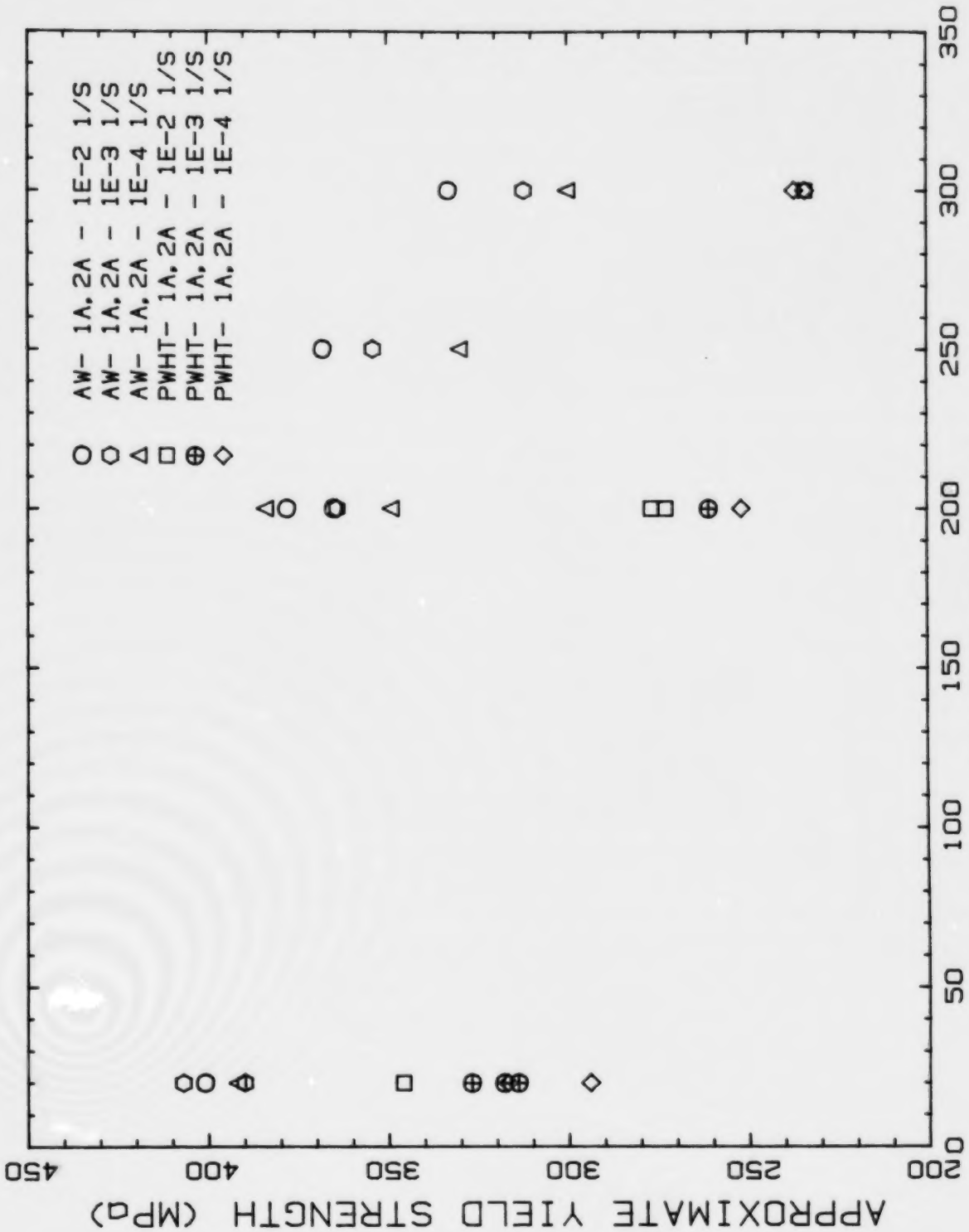

FIGURE 18(a): PLOTS ILLUSTRATING THE VARIATION OF APPROXIMATE 0.2% OFFSET YIELD STRENGTH WITH TEMPERATURE AT CONSTANT APPLIED STRAIN RATE IN AW-1A, AW-2A, PWHT-1A AND PWHT-2A MATERIALS.

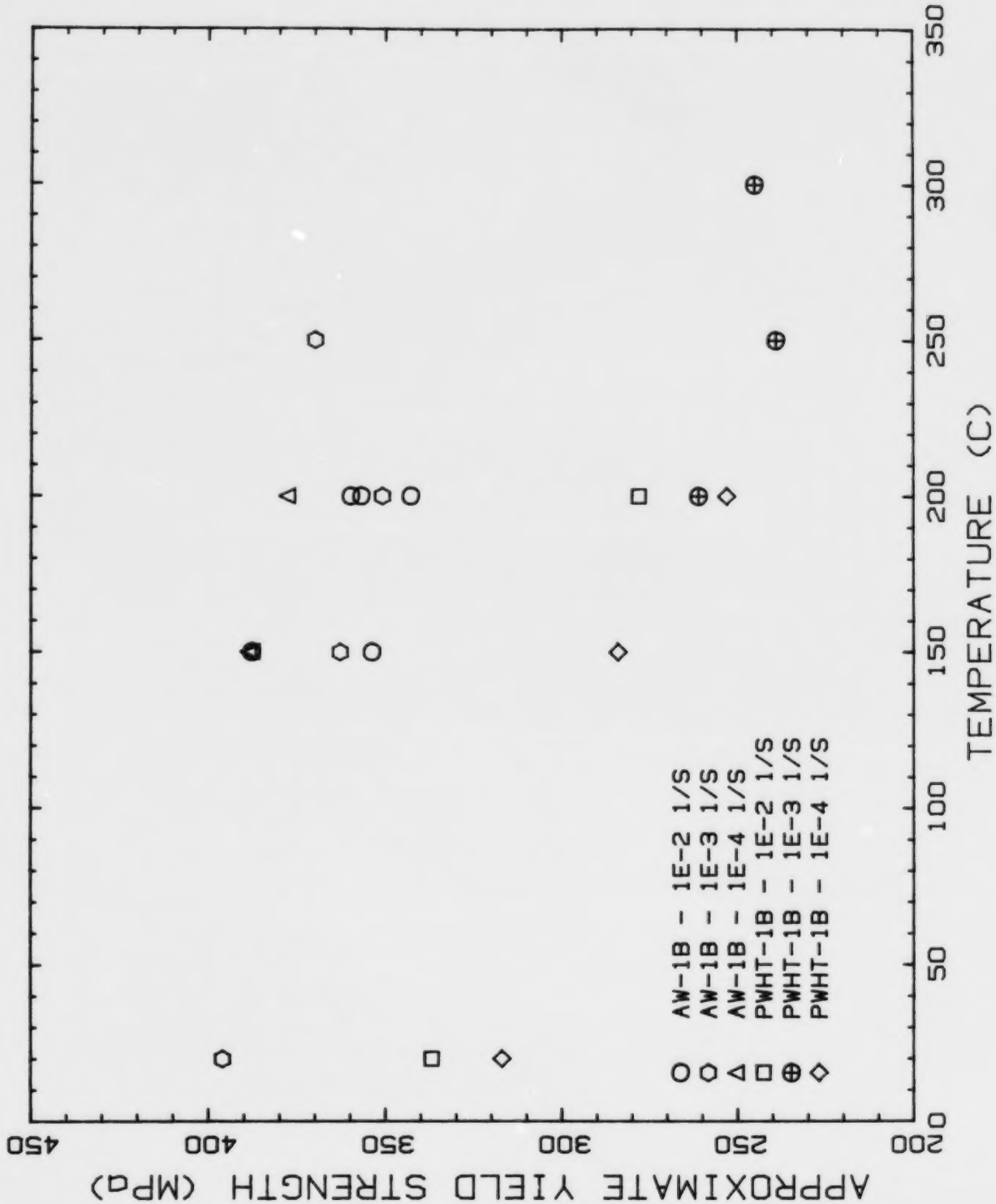

FIGURE 18(b): PLOTS ILLUSTRATING THE VARIATION OF APPROXIMATE 0.2% OFFSET YIELD STRENGTH WITH TEMPERATURE AT CONSTANT APPLIED STRAIN RATE IN AW-1B AND PWHT-1B MATERIALS.

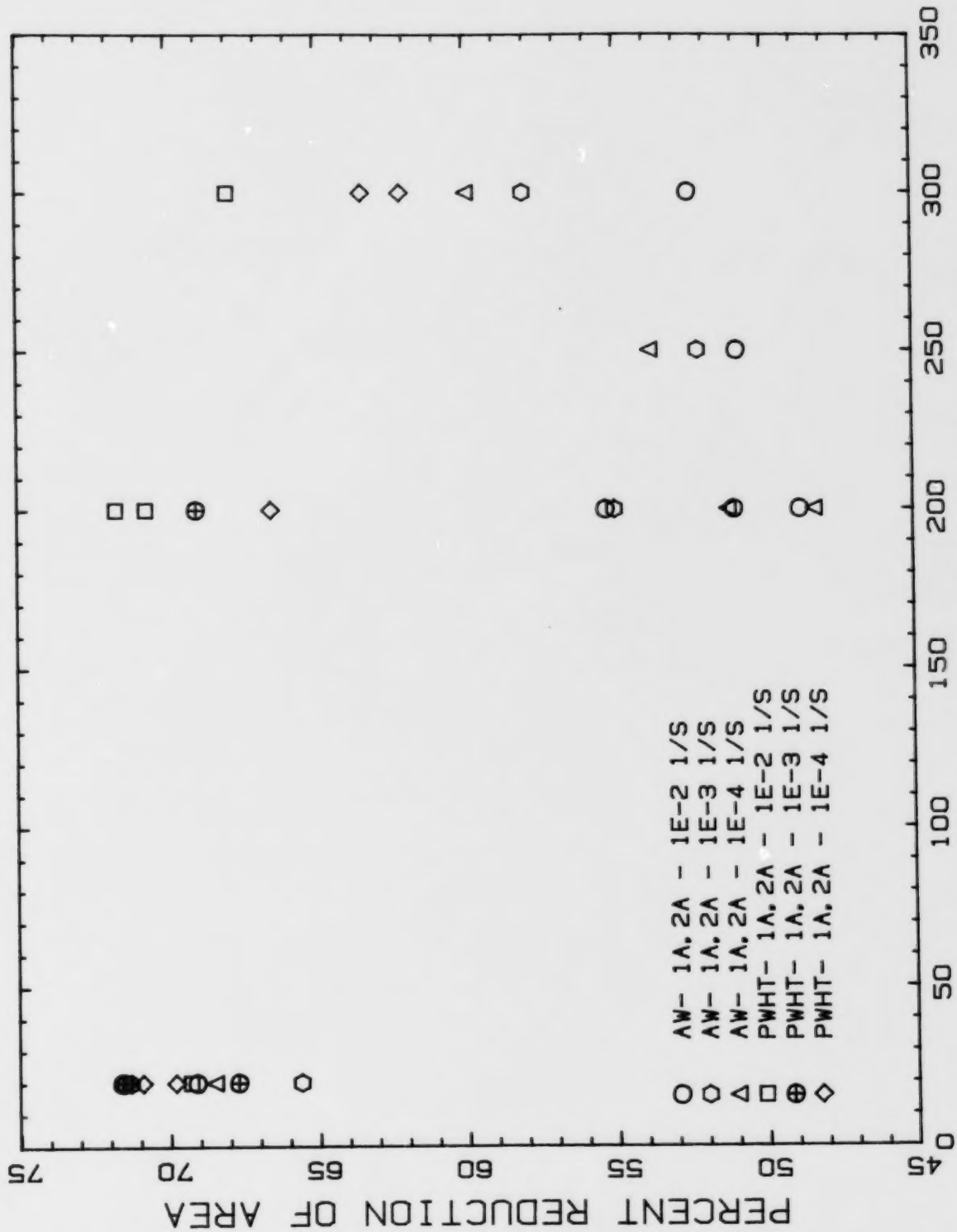

FIGURE 19(a): PLOTS ILLUSTRATING THE VARIATION OF PERCENT REDUCTION OF AREA WITH TEMPERATURE AT CONSTANT APPLIED STRAIN RATE IN AW-1A, AW-2A, PWHT-1A AND PWHT-2A MATERIALS.

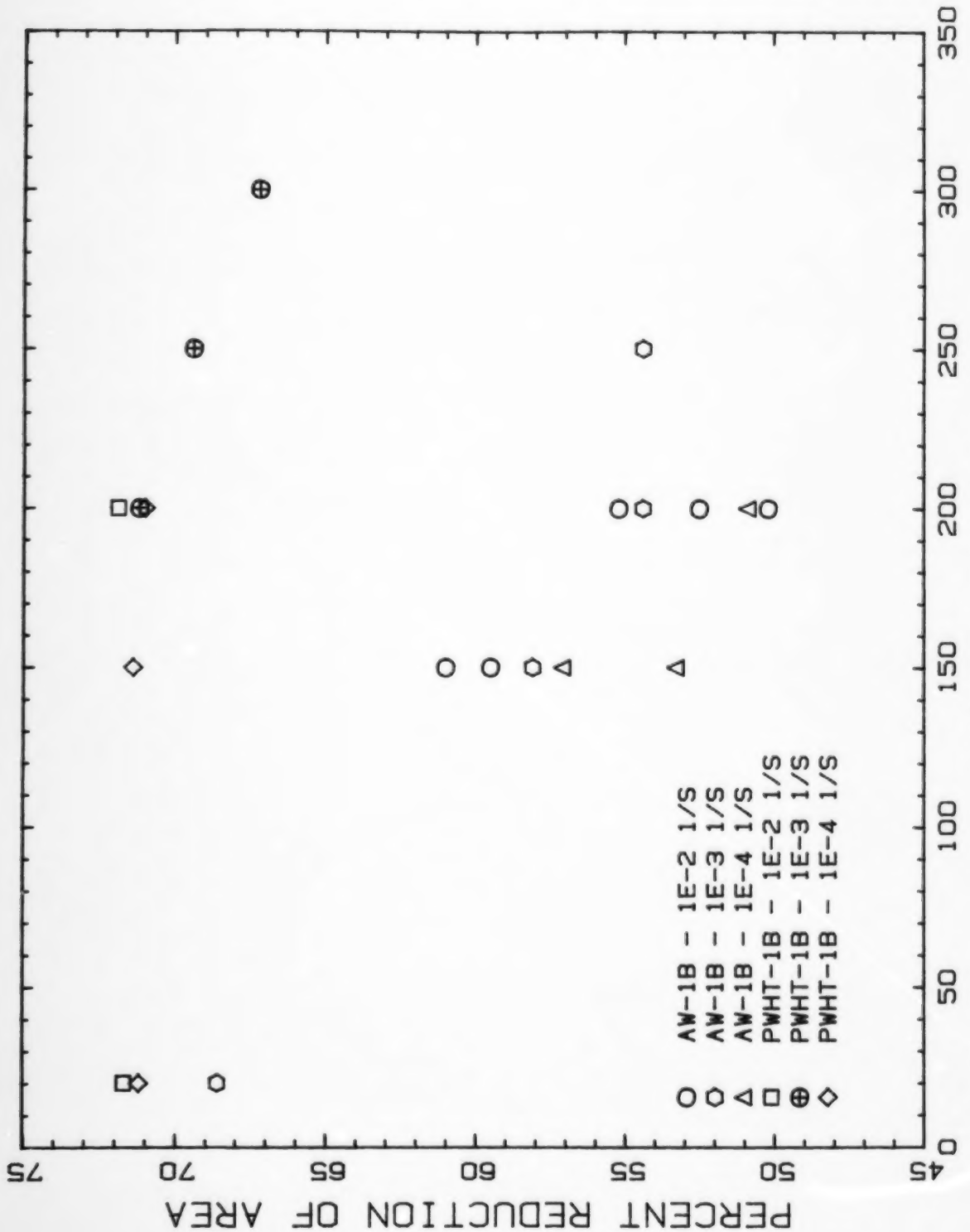

FIGURE 19(b): PLOTS ILLUSTRATING THE VARIATION OF PERCENT REDUCTION OF AREA WITH TEMPERATURE AT CONSTANT APPLIED STRAIN RATE IN AW-1B AND PWHT-1B MATERIALS.

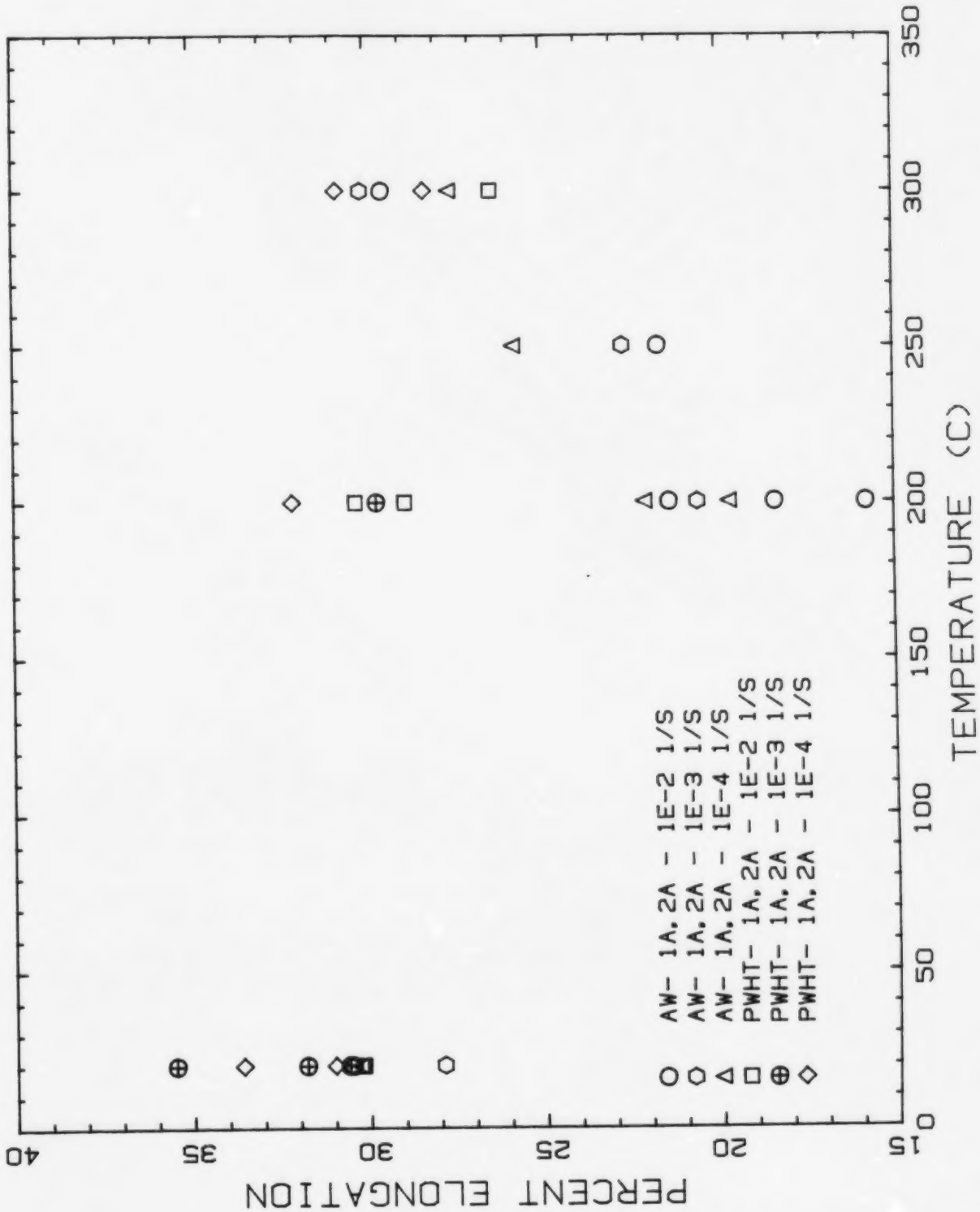
PERCENT ELONGATION
TEMPERATURE (C)
AW- 1A, 2A - 1E-2 1/S
AW- 1A, 2A - 1E-3 1/S
AW- 1A, 2A - 1E-4 1/S
PWHT- 1A, 2A - 1E-2 1/S
PWHT- 1A, 2A - 1E-3 1/S
PWHT- 1A, 2A - 1E-4 1/S

FIGURE 20(a): PLOTS ILLUSTRATING THE VARIATION OF PERCENT ELONGATION WITH TEMPERATURE AT CONSTANT APPLIED STRAIN RATE IN AW-1A, AW-2A, PWHT-1A AND PWHT-2A MATERIALS.

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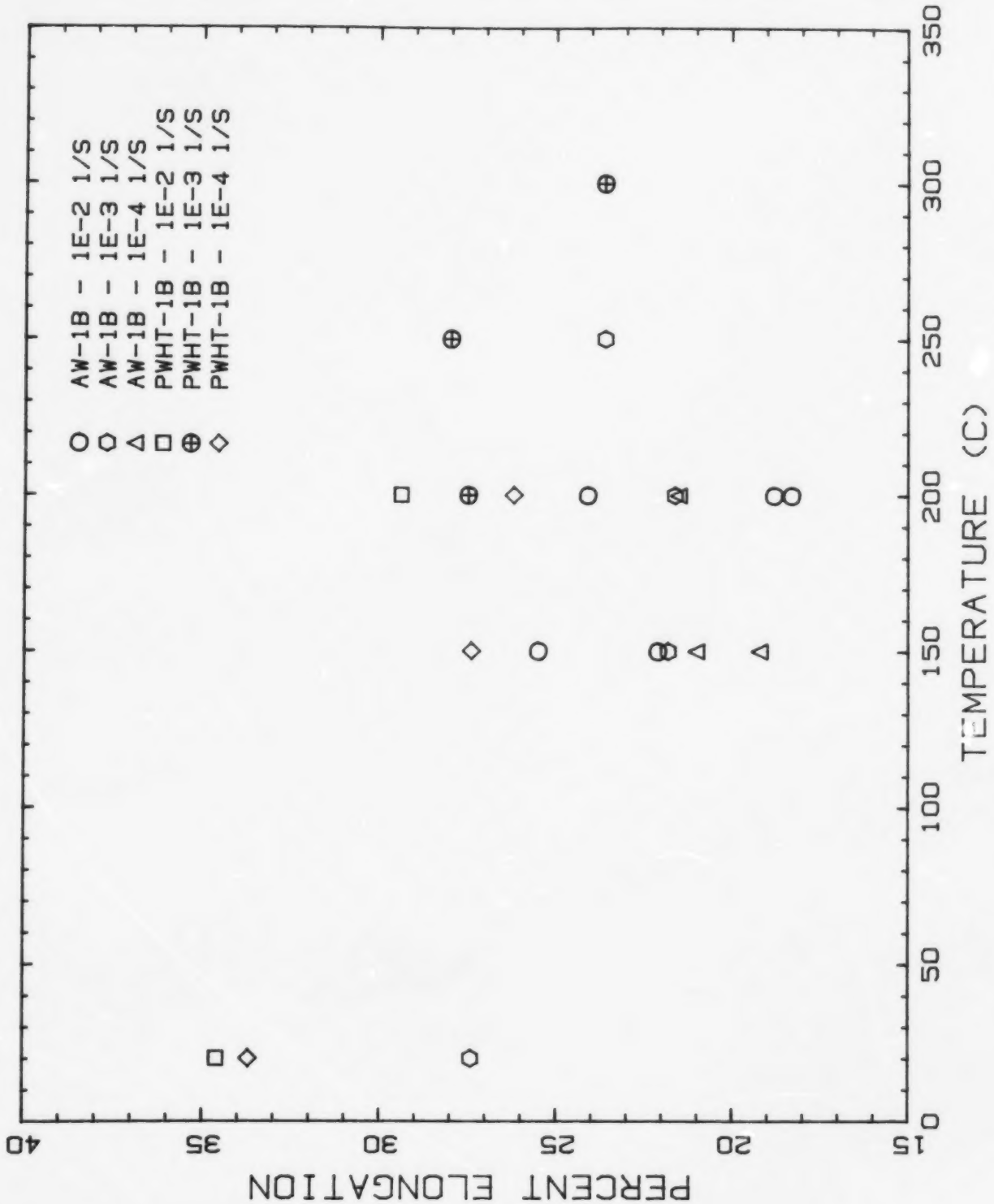

FIGURE 20(b): PLOTS ILLUSTRATING THE VARIATION OF PERCENT ELONGATION WITH TEMPERATURE AT CONSTANT APPLIED STRAIN RATE IN AW-1B AND PWHT-1B MATERIALS.

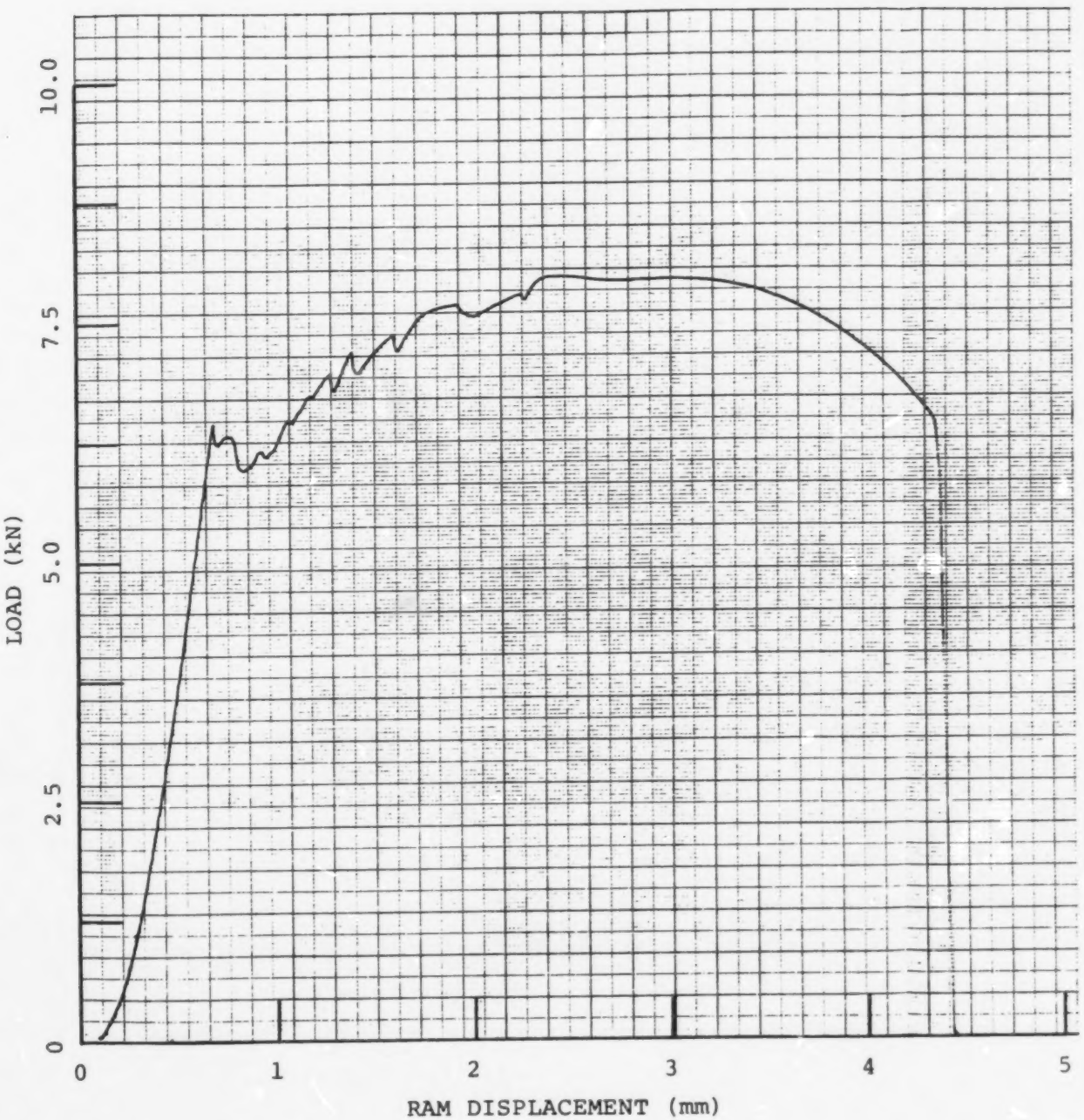

FIGURE 21: LOAD VS RAM DISPLACEMENT PLOT SHOWING WIDELY SPACED DOWNWARD DROPS IN THE FLOW CURVE. AW-1B MATERIALS WAS TESTED AT 150 C AT AN APPLIED STRAIN RATE OF 1E-2 1/S.